AD-A271 172

‖‖‖‖‖‖‖‖‖‖‖‖‖

Fidelity Assessment of a UH-60A Simulation on the NASA Ames Vertical Motion Simulator

Adolph Atencio, Jr.

DTIC
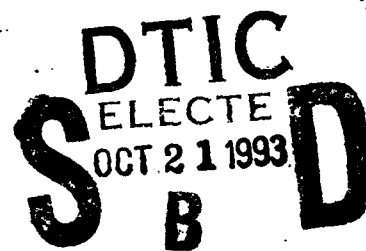**ELECTE**
OCT 2 1 1993
S B D

September 1993

US ARMY
AVIATION and
TROOP COMMAND

DISTRIBUTION STATEMENT
Approved for public release
Distribution Unlimited

93-25369
‖‖‖‖‖‖‖‖‖‖‖‖

NASA
National Aeronautics and
Space Administration

93 10 20 085

Fidelity Assessment of a UH-60A Simulation on the NASA Ames Vertical Motion Simulator
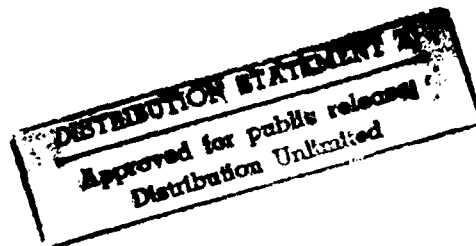
Adolph Atencio, Jr., Aeroflightdynamics Directorate, U.S. Army Aviation and Troop Command, Ames Research Center, Moffett Field, California

September 1993

US ARMY
AVIATION and
TROOP COMMAND

NASA

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

CONTENTS

NOMENCLATURE

A/C	aircraft
accel	acceleration, ft/sec^2, deg/sec^2
ADI	Attitude Director Indicator
AEFA	U.S. Army Aviation Engineering Flight Activity
AFCS	automatic flight control system
AFDD	Aeroflight Dynamics Directorate
ALT	radar altitude, ft, simulated aircraft
ALTD	altitude dot, rate of change of altitude, ft/sec
ATT	attitude, deg
BU	bob-up
CGI	computer generated image display
CIFER	Comprehensive Identification From FrEquency Responses
COLLSTK	collective stick, in.
dB	decibel, 20 log (magnitude ratio)
DIG-1	Singer—Link Digital Image Generator-1
DISPL	displacement
DQS	dash/quick stop
FPS	flight-path stabilization
FOV	field of view
FRESPID	Frequency RESPonse IDentification
FSAA	Flight Simulator for Advanced Aircraft
FWD	forward
Gxx MAG	auto-power spectral density, magnitude, dB
HQR	handling qualities rating
HQSF	handling qualities sensitivity function
I-CAB	integrated cab
LATSTK	lateral cyclic stick position, in.
mrad	milliradian
NOE	nap of the earth
PB	roll rate body axis, deg/sec
PHI	roll attitude, deg, simulated aircraft
PITCHATT	pitch attitude, deg
PIO	pilot-induced oscillation
PSD	power spectral density
PSFU	roll rate follow-up simulator motion system, rad/sec
PSI	yaw attitude, deg, simulated aircraft
QB	pitch rate body axis, deg/sec

QSFU	pitch rate follow-up simulator motion system, rad/sec
RADALT	radar altitude, ft, flight test value
RB	yaw rate body axis, deg/sec
RMS	root mean square
ROLLATT	roll attitude, deg, flight test value
RSFU	yaw rate follow-up simulator motion system, rad/sec
SAS	stability augmentation system
SS	side step
THET	pitch attitude, deg, simulated aircraft
VB	velocity in y-axis direction, body axes, ft/sec, simulated aircraft
VICB	instrument-corrected airspeed (from boom), knots, flight test value
VMS	Vertical Motion Simulator
VXBIKT	velocity in x-axis direction, knots, simulated aircraft
VZFU	velocity in z-direction, follow-up simulator motion system
XA	lateral cyclic stick position, in., simulated aircraft
XB	longitudinal cyclic position, in., simulated aircraft
XC	collective stick position, in., simulated aircraft
XCGREF	longitudinal reference position, ft, simulated aircraft
XPEDLT	pedal controller position, in., simulated aircraft
XTTLV	laser distance in lateral direction from reference, ft, flight test
YAWRATE	yaw rate, deg/sec, flight test value
YTTLV	laser distance in longitudinal direction from dish, ft, flight test
ZTTLV	Laser measurement of height above ground, ft, flight test
δ	controller
δ_{coll}	collective stick position, in.
δ_{lat}	lateral cyclic stick position, in.
δ_{long}	longitudinal cyclic stick position, in.
δ_{ped}	pedal position, in.
Ψ_{total}	root mean square value for auto-power spectral density
ω_c	crossover-frequency/cutoff-frequency, rad/sec

SUMMARY

Helicopter handling qualities research requires that a ground-based simulation be a high-fidelity representation of the actual helicopter, especially over the frequency range of the investigation. This experiment was performed to assess the current capability to simulate the UH-60A Black Hawk helicopter on the Vertical Motion Simulator (VMS) at NASA Ames, to develop a methodology for assessing the fidelity of a simulation, and to find the causes for lack of fidelity. The approach used was to compare the simulation to the flight vehicle for a series of tasks performed in flight and in the simulator. The results show that subjective handling qualities ratings from flight to simulator overlap, and the mathematical model matches the UH-60A helicopter very well over the range of frequencies critical to handling qualities evaluation. Pilot comments, however, indicate a need for improvement in the perceptual fidelity of the simulation in the areas of motion and visual cuing. The methodology used to make the fidelity assessment proved useful in showing differences in pilot workload and strategy, but additional work is needed to refine objective methods for determining causes of lack of fidelity.

1 INTRODUCTION

The quality of simulation in ground-based facilities continues to be of concern as aircraft systems become more complicated and more costly to develop for actual flight. Simulation fidelity assessment is an ongoing discipline to assure that data collected during experiments meet expectations and have validity (refs. 1–5). High-fidelity simulation requires that the simulation must possess not only good objective fidelity (the degree to which the simulator reproduces measurable aircraft states or conditions), but must have good perceptual fidelity (the degree to which the pilot perceives the simulator to replicate the aircraft states or conditions). The assessment of a simulation to determine the causes of a lack of fidelity is complicated by the interface between the pilot and the simulator systems. The pilot–vehicle system for flight versus the pilot–simulated-vehicle system for simulation is illustrated by a simple block diagram in figure 1. The diagram (a slight modification from reference 1) shows the basic loops for flight and simulation and their differences. In the flight case (a), the pilot attempts to execute the task commands by relying on piloting technique and feedback stimuli from the vehicle motion. Visual and motion cues form the pilot's perceived states, and they are not corrupted. In the simulator case (b), the pilot has the same desired states and acts accordingly to achieve those states by relying on piloting technique, reference to memory (flight experience), and feedback stimuli (visual and motion cues) from the simulated aircraft. The cues the pilot receives from the simulated world are filtered through the systems (math model, motion system, visual system) needed to produce the illusion of actual flight.

A method is needed to evaluate the effects of these artificial additions in the simulator pathway that the pilot uses to perceive the state of the aircraft. To date, these effects have been measured both quantitatively and qualitatively. Quantitative measurements are used to evaluate how well the simulated aircraft replicates the aircraft response to control inputs (objective fidelity). Qualitative measurements are used to determine how well pilots perceive the simulator to replicate the aircraft. Objective fidelity may be determined by comparing time history data from actual flight and simulation, as well as using frequency response techniques to show how well the simulator is dynamically equivalent to the aircraft. These comparisons check the validity of the underlying assumptions used to model complicated systems for real-time simulation. Pilot perception of simulator fidelity is crucial to acceptance of the simulated aircraft as a viable representation of the real aircraft. This is generally done in the form of a handling qualities assessment. The pilot analyzes the mental and physical workload and scanning patterns when flying a task with specific performance standards. The degree to which the pilot is able to meet the desired performance standard with the aircraft systems and level of workload required results in a handling qualities rating (HQR) (ref. 6). HQRs for the same task from the aircraft and simulator may be compared to determine relative pilot–vehicle performance and compensation required as perceived by the pilot. In addition, pilot comments regarding system performance can be used as a guide for further investigation.

This report gives results from a fidelity assessment of the UH-60A simulation using the Vertical Motion Simulator (VMS) at NASA Ames. The methods applied to assess the fidelity of the simulation include the comparison of the actual aircraft to the simulator using quantitative and qualitative measurements.

The author wishes to thank the many people who made contributions to this experiment. The flight test was under the direction of Ed Seto of NASA. On-site flight test operations at Crows Landing were under the direction of Ed Farr. The five test pilots were Lt. Col. Rickey Simmons, (Aeroflight Dynamics Directorate (AFDD) Project Pilot); Warren Hall, NASA test pilot; Maj. Dave Downey, U.S. Army Aviation Engineering Flight Activity (AEFA) project pilot; Flt. Lt. Andrew Tailby, detailed to AEFA from the Royal Airforce; and Mike Meyers, from AEFA. The SYRE contractor staff provided assistance in the setup and operation of the experiment on the VMS. Simulation engineers from SYRE helped code the Gen Hel mathematical model for real-time operation and were on-site operators of computer and data collection apparatuses.

Technical assistance for the Gen Hel mathematical model setup was provided by Mark Ballin (NASA). Richard Bray (NASA, retired) provided assistance in VMS system setup and helped conduct the 1989 experiment on the VMS. Mark Tischler (AFDD) provided the author with assistance in the use of the power spectral density functions and pilot cut off frequency calculations.

Many others contributed, but are too numerous to name. Their assistance is appreciated.

2 HISTORY OF UH-60A BLACK HAWK SIMULATION VALIDATION

The UH-60A is a four-bladed single-main-rotor utility helicopter (fig. 2). It has a four–bladed tail rotor with the tail-rotor shaft canted 20 deg upward from horizontal. The helicopter has a movable horizontal stabilator located on the lower portion of the tail rotor pylon. It is powered by two T700-GE-700 (T700) turbo-shaft engines and has fixed-wheel-type non-retractable landing gear. Descriptions of the aircraft systems and the flight control system are contained in references 7–9. A short description of the flight control system is contained in appendix A. The Black Hawk simulation is based on the UH-60A Gen Hel mathematical model, which has been extensively used at NASA Ames to study handling qualities.

The first full validation experiment on the UH-60A simulation was performed in 1982. The experiment was done with the cooperation of the U.S. Army and NASA, and with the help of Sikorsky Aircraft Company and Systems Technology, Inc. (ref. 10).

The real-time UH-60A simulation was synthesized from the Gen Hel mathematical model of the UH-60A purchased from Sikorsky Aircraft Company in 1980 (ref. 7). The Sikorsky contract provided help to implement the real-time model for a simulation on the NASA Ames VMS and provided data for validating the mathematical model against flight.

Systems Technology, Inc., provided assistance for designing a simulation experiment to both validate the simulation and to assess the fidelity of the simulation. The effort involved the development and application of tools and methods for the fidelity assessment. The resulting experiment depended on a comparison of simulator and flight results.

Flight tests to support the simulation were performed by the AEFA, now called the Airworthiness Qualification Test Directorate (AQTD), at Edwards Air Force Base, California (ref. 8). The flight tests consisted of flying the UH-60A (fig. 2) in a series of tests to gather mathematical model verification data and to fly and evaluate the fidelity assessment tasks used in the simulation. The fidelity assessment tasks were designed to emulate tasks performed by U.S. Army helicopter pilots when flying nap-of-the-earth (NOE) combat maneuvers. The maneuver performance in the Edwards flight tests served as the data to which the task performance in the simulator was compared. To establish a comparison, the tasks flown at Edwards were subjectively evaluated by the test pilots using the Cooper–Harper handling qualities rating scale (ref. 6). In addition, measurements were taken to establish a time history comparison between simulation and flight and to devise other objective comparisons to verify pilot subjective evaluations between simulation and flight.

This first attempt at validation indicated that the simulation needed work in order to improve the fidelity to be more representative of the aircraft (refs. 10–12). Conclusions indicated significant differences in how the pilots executed tasks in the simulator and in flight. These differences were, in part, attributed to disparate motion/visual cues and a lightly damped aircraft in the simulator. Figure 3 compares pilot subjective HQRs for several fidelity assessment tasks. These ratings from the 1982 simulation show that there is no overlap in the ratings from flight to simulator for any of the tasks. Also, the ratings for tasks done in flight are generally in Level 1 (HQR from 1 to 3.5), but the ratings from tasks done in the simulator were generally in Level 2 (3.5 to 6.5). Subsequently, additional work

has been performed to improve the simulation of the UH-60A on the VMS.

After the 1982 simulation, it was thought that the dynamics and damping characteristics of the simulation mathematical model could be improved with the addition of more sophisticated modeling of component systems and an upgrade of some existing systems. That work has been done at NASA Ames (refs. 13 and 14) and through additional contracts to Sikorsky (ref. 15). Part of the NASA Ames effort involved a rework of the rotor model to improve the stability in real-time operation (refs. 16 and 17) and to modify the collective primary servo dynamics to improve collective response. The propulsion system was updated to the standards of T700 engine using a model obtained from NASA Lewis, and the gear box model was expanded to accommodate the dynamics of the T700 engine model.

In 1986, the U.S. Army recorded several accidents/incidents that had unexplained origins, but were thought to involve stabilator runaway. The UH-60A helicopter simulation was thought to have sufficient maturity and a high enough fidelity to help in determining the causes of these accidents/incidents. In preparation for these tests, the stabilator control model was improved for the simulations with the addition of flight data for specific trim conditions and dynamic responses (ref. 18). Also, the flight-path stabilization (FPS) model was expanded to be more representative of the aircraft, including full operation of back-driven control positions, trim beeper switches, and expansion of the of FPS sample-and-hold on–off logic. In addition, pedal microswitches were added to the cab so that turn coordination and heading hold logic could be employed like the aircraft. The investigations were performed in the summer of 1986. This simulation provided useful information on stabilator effects.

The most recent flight tests (July 1989) provided extensive data for assessing the mathematical model through the use of piloted frequency sweeps. These assessments have led to changes in the rotor inflow model and to other changes that are expected to improve the mathematical model beyond the form used in this experiment (ref. 19).

The simulation fidelity assessment and validation experiment was designed to determine the state of the simulation and to experiment further with fidelity assessment techniques. This paper will address the techniques applied and present the assessment and experiment results.

3 OBJECTIVES AND APPROACH

The simulation of the UH-60A had two objectives:

1. To assess the current ability to simulate the UH-60A at NASA Ames, and

2. To develop and apply methods to assess the fidelity of a simulation and to determine the causes for lack of fidelity.

The approach was to compare the simulated aircraft to the UH-60A. The comparison was made using the following procedure:

1. The mathematical model was a given for the experiment. The model was programed for real time simulation and was checked statically and dynamically against both the non-real-time master model and against data from the aircraft. After the initial setup, checkout, and verification, the model remained in a fixed configuration for the experiment.

2. A series of tasks was defined with limited aggressive maneuvering and with simple visual cuing to fit within the motion and visual envelope of the VMS.

3. The tasks were flown by test pilots in back-to-back evaluation in flight tests and in the simulator.

4. Pilot evaluation of task performance was done using subjective handling qualities ratings and comments.

5. Objective fidelity measurements were made using recorded data and analysis tools to sort out specific pilot comments regarding a lack of fidelity in the simulation. For example, documentation of the simulated aircraft dynamic response compared to the aircraft was done using the piloted frequency sweep technique.

4 EXPERIMENT SETUP

The main thrust of the fidelity assessment was to compare pilot–vehicle performance and workload in the simulator to that experienced in the aircraft. The flight tests were conducted concurrently (on the same day, if possible) with the simulation so pilots could have a fresh experience of flying the aircraft before performing the same tasks in the simulator.

The experiment was set up to use a series of fidelity assessment tasks. Three tasks were selected for evaluation. The selected maneuvers were the bob-up/bob-down (bob-up), the side step, and the dash/quick-stop. These maneuvers were done in the 1982 experiment, thus a comparison can be made with those

results. The bob-up and side step maneuvers were selected because they are handling qualities tasks with easily quantified task constraints and because of the ability to set up a simulator task that duplicated the flight task. The tasks can be designed so that each pilot approaches the task in nearly the same manner. To assure that the task would be repeatable, a special set of "hover boards" were used for the flight tests, and an exact copy of the boards was modeled in the computer generated visual scene in the simulator. The dash/quick-stop maneuver was selected because it is an aggressive task that pushes the simulated field of view to the limit and requires the pilot to closely manage spatial position throughout the task. The maneuver was designed to be a quick dash from a hover to 60 knots followed by a quick stop back to hover. The quick stop was done as a rotation about the tail wheel while simultaneously trying to avoid excessive altitude gain during the stop.

4.1 Evaluation Tasks

The flight tasks used for the fidelity assessment were originally set up using the simulator to get reasonable levels of aggressiveness without exceeding the simulator envelope. The criteria made the task aggressive and challenging so that both the aircraft and the simulator would have to be flown with skill and care. A time constraint was added to give the pilots a sense of urgency in the task and to make sure all pilots tried to perform the tasks with a similar level of aggression. The numbers selected from the simulator were evaluated in the flight test to verify the assumptions and were found to meet the criteria.

The procedure followed in the flight test and simulator was for each pilot to perform a task at least three times. In the flight test, the pilot evaluated the task on each attempt. This approach was repeated in the first simulation. In the second simulation, the pilots performed the task three times in succession before rating the series. It was found that both methods were consistent with little or no variation in ratings. The Cooper–Harper handling qualities rating scale (ref. 6) (fig. 4) was used with the performance criteria given below. Pilot comments were recorded with each rating and a questionnaire was used to elicit more comments in specific areas during the flight test and the simulation. A questionnaire from the flight test and the simulator is shown in figure 5.

4.1.1 Hover Boards

Two tasks (bob-up and lateral side-step) were performed using the hover boards as the primary visual reference. The hover boards were designed to provide a visual cuing aid for the pilot that could be easily duplicated in a computer-generated visual scene. The boards were originally designed to perform a precision hover in the Harrier aircraft for a NASA research program (ref. 20). The hover boards are two identical targets (optical sights) that are spaced 40 ft apart on centers. A structure to space and support the boards was designed to allow the boards to be spaced either vertically or horizontally (figs. 6 and 7). The hover board optical sight is shown in figure 8. The background board is a 2.25 ft by 10 ft white rectangle. The background board has a special pattern that with the standoff structure makes the optical sight. The standoff structure is a set of slim rectangular black parallax boards positioned 2 ft from the background board surface at their closest point and angled 65 deg with respect to the background board surface. One board is angled to the right and the other to the left. They are separated 0.97 ft at the closest point. A plan view of the board and standoff structure shows the parallax boards forming a "V" centered on the background board. The top of the V is 7.25 ft wide and the bottom of the V is cut off so that there is a width of 0.97 ft and the cutoff base is 2 ft from the background board. The beam that supports the hover boards at the 40 ft spacing is painted in a 2 ft alternating white and black pattern. The pattern was called a ladder when the boards were in the vertical position.

The optical sight is used as follows (fig. 8):

1. When the pilot's eye is lined up with the center line of the optical sight at a distance of 66 ft from the background surface, perfect alignment shows a broad black stripe the width of the parallax boards centered on the background with the corner tips of the stripe just touching the inside corners of the two broad black stripes on the outside edges at each end of the background board. The center space on the background board between the end stripes is filled with a red stripe about 3/4 the length of the end stripes (from the end inward) with the remaining space left white. The alignment pattern is completed with a small white rectangular box on each tip of the parallax board.

2. If the pilot remains centered on the optical sight, but drifts toward the target, the white box begins to

shrink until only the red remains at the tips of the parallax board.

3. If the pilot remains centered on the optical sight, but drifts away from the target, the parallax board separates from the outside edge black stripes and drifts into the white of the background board. When the drift back gets to a distance of 106 ft, a vertical black stripe shows on each parallax board tip.

4. If the pilot remains centered on the target, but drifts either right or left, the parallax effect takes over and the pilot sees an uneven pattern. White from the background board breaks the parallax stripe in the middle portion and the new white stripe increases in width in the opposite direction of the drift. The parallax boards appear to change in length with the direction of drift board appearing shorter.

5. If the pilot remains centered on the target, but drifts either up or down, the parallax boards' tips appear to move up or down (in an exaggerated fashion) in the opposite direction of the motion. The parallax board tips may appear to merge with the broad black stripes on the outside edges on each end of the background board and the center of the background board may be exposed showing the support for the parallax boards.

During the UH-60A flight tests, a standoff distance from the boards was set at 106 ft for safety reasons because of the spinning rotor. This distance was also used for the simulation. Initial alignment on the boards was done using a spotter on the ground in the flight test to get correct longitudinal distance and to prevent excessive drift toward the boards. The simulation set the 106 ft eye-point distance in the initial condition setup file so that the pilot was initialized in hover at the correct distance. Although the vertical stripes placed on the parallax board tips were the pilot's reference for longitudinal placement from the boards, they proved to be inadequate since the primary target design relied heavily on the broad black stripes on the background board for reference. In retrospect, it would have worked better to have filled the broad stripes to the vertical lines.

4.1.2 Bob-Up Maneuver

The bob-up maneuver was performed starting from a stabilized hover at the lower hover board, then rapidly bobbing-up 40 ft to the upper hover board and stabilizing. The bob-up and stabilization should be completed within 10 sec. After stabilization, the top

position is held for 5 sec. Next, the pilot rapidly bobs down 40 ft to the lower hover board and stabilizes within 10 sec. The hover position is held for 20 sec after stabilization.

Performance Standards

Desired:

1. Altitude excursions within ±3 ft from hover board center after stabilization, **and**

2. Heading excursions within ±5 deg of desired heading throughout, maneuver, **and**

3. Lateral excursions within hover board width after stabilization.

Adequate:

1. Maintain desired performance taking more than 10 sec to bob up (or down) and stabilize, **or**

2. Maintain desired performance for most of task except for occasional excursions which exceed, but are followed by return to, desired performance limits.

4.1.3 Side-Step Maneuver

The side-step maneuver was performed starting from a stabilized hover at the left hover board, then rapidly translating 40 ft to and stabilizing at the right hover board. The stabilized hover is held for 20 sec at the right hover board. Repeat the maneuver moving to the left instead of the right.

Performance Standards

Desired:

1. Complete translation and stabilization within 7 sec and with no objectionable oscillations,

2. Maintain altitude excursions within ±3 ft from hover board centerline throughout the maneuver,

3. Maintain heading excursions within ±5 deg of desired heading throughout the maneuver, **and**

4. Maintain lateral excursions (with reference to the pilot station) within hover board width after stabilization is reached.

Adequate:

1. Maintain the desired performance taking more than 7 sec to translate to right (or left) and then stabilizing, **or**

2. Maintain desired performance for most of task except for occasional stable excursions which exceed, but are followed by a return to, desired performance limits.

5

4.1.4 Dash/Quick-Stop Maneuver

The dash/quick-stop maneuver was to be performed by establishing a 20 ft hover, then initiating a rapid acceleration to 60 knots followed by a rapid deceleration/quick-stop to a 20 ft hover. The stabilized hover is held for 20 sec.

Performance Standards

Desired:
1. Achieve maximum acceleration as quickly as possible maintaining a 20 ft altitude (±5 ft) above the surface. At 60 knots, begin a quick stop by rotating about the tail wheel.
2. Avoid excessive ballooning (>50 ft altitude) during deceleration to the quick stop.
3. Maintain heading within ±10 deg, **and**
4. Perform the dash/quick-stop to hover in 30 sec or less.

Adequate:
1. Perform dash/quick-stop maneuver in more than 30 sec while maintaining desired performance boundaries, **or**
2. Exceed dash height constraint by more than ±5 ft, **or**
3. Exceed heading constraint by more than ±10 deg while maintaining other constraints.

4.2 Flight Test

The flight tests were completed in four days (July 11–12 and July 18–19, 1989) at the NASA Ames flight test facility at Crows Landing Naval Air Station (elevation 141 ft) in the Central Valley of California. The test aircraft was a UH-60A Black Hawk helicopter. The aircraft was in transition for a new test program, thus it had been stripped and had only limited data instrumentation. It was flown at 14,400 pounds (center of gravity at 355 in.) which included two pilots, a flight test engineer, and data recording equipment.

The flights were planned for early morning to avoid wind and turbulence. This was done because the simulation mathematical model did not include an atmospheric turbulence model. Although the wind was not always calm, it was generally light with little turbulence. Figure 9 summarizes the weather conditions during the flight tests. Temperature, mean wind velocity and standard deviation, and wind direction are listed.

Pilots from NASA Ames, AFDD, and AQTD at Edwards Air Force Base participated in the tests. Each day, two pilots flew the UH-60A. Each pilot flew the task from the pilot right-side seat. July 11–12 were used for the bob-up/bob-down and the dash/quick-stop tasks and July 18–19 were used for the side-step task. All tasks were performed on a side apron to avoid interference with other flights in the area. Since the ramp area was out of the normal traffic area, it was a safe place for the crane used to rig the hover boards. The NASA test control center was near the same ramp and radar and laser tracking was done from the center. The test center also had facilities for telemetry and display of data from the aircraft and a communications link with the aircraft. All performance data were recorded on the aircraft's digital tape machine for later analysis.

4.3 Simulation

The simulation was performed in the NASA Ames six-degrees of freedom VMS. The Gen Hel Black Hawk helicopter mathematical model was resident on the AD-100 host computer and linked with the Singer–Link Digital Image Generator (DIG-1) computer and the motion computer. In addition, aural cues, a seat shaker, and a full cockpit (set up for pilot station only) were provided for the simulation. The 1989 experiment was performed concurrently with a flight test to enable a one-to-one comparison between flight and simulator. The performance data from the 1989 simulation were lost due to an error in the data retrieval software on the AD-100 computer, which gave a signal that data from the simulation were being recorded when, in fact, no data were recorded. The subjective HQR data along with some strip chart data are the only surviving data from the simulation. The January 1990 experiment was run specifically to gather objective measurement data. The January simulation did not have a concurrent flight test. Other differences in hardware and software for the two simulations included the substitution of the N-CAB simulator cockpit in place of F-CAB cockpit, and some minor errors in execution of the math model were fixed between simulations.

4.3.1 Mathematical Model

The mathematical model calculates the aircraft state and its derivatives from pilot control inputs. It is central to the simulation, and all other systems (e.g., visual, motion, force feel) receive and use output from

the model to emulate the UH-60A helicopter. Both the NASA Ames real time version and the Sikorsky version of the Gen Hel mathematical model were kept current through the many changes done under contract. Figure 10 illustrates the main components of the mathematical model. The following paragraphs describe the basic model and are quotes from personal notes provided to the author by Mark Ballin.

"The Gen Hel model is a nonlinear representation of a single main rotor helicopter, accurate for a full range of angles of attack, sideslip, and rotor inflow. Six rigid-body degrees of freedom are modeled as well as the main rotor flapping, lagging, air mass, and hub rotational speed degrees of freedom. Since it is a modular system, each major force and moment producing element is treated as a independent entity. The framework of the program is the interfacing of these elements. All interfaces are physical quantities such as forces, moments, attitudes, body-fixed velocities, and downwash velocities."

"A blade-element approach is used to model each main rotor blade. Total rotor forces and moments are produced by summation of forces from each blade, which are determined from aerodynamic, inertial, and gravitational forces. Aerodynamic forces are computed from angle of attack and dynamic pressure acting on each blade segment as based on the orthogonal velocity components. These components are determined as functions of blade azimuth, lag, and flap angles, local velocity of the blade segment, and on local downwash. Downwash is approximated to have a first harmonic distribution as a function of wake skew angle. Blade inertial and gravitational forces are computed from blade rotational velocity, lagging and flapping velocities and accelerations, and blade position. No dynamic twisting or bending of the blades is modeled, although a preformed blade twist is represented through adjustment of geometric pitch of each segment. The summation of forces act on the airframe at the blade hinge and lag damper locations. Rotor moments result from blade hinge and lag damper offset from the main rotor shaft."

"Tail rotor thrust is represented by linearized Bailey theory (ref. 21). Interference effects from the aerodynamic modules are accounted for as empirically determined blockage factors. Main rotor downwash is used to modify the tail rotor inflow. The aerodynamics of the fuselage, stabilator, and vertical tail pylon are each represented in separate modules so that nonlinear interference effects of the main rotor and interference

between components are modeled separately. Aerodynamic function tables were developed from wind tunnel test data, and reference 22 was used to extrapolate and modify the available data."

Initial interaction with the mathematical model is through the cockpit controllers. The cockpit on the simulator is one of several cab facilities available for simulation. A cockpit is set up to represent the simulated aircraft in a functional manner. That is, the pilot station is set up to be a realistic representation of the aircraft in terms of controller location and flight instrument layout and has a visual display for outside reference to spatial position.

4.3.2   Simulator Cockpit

The UH-60A simulations used the F-CAB in July 1989 and the N-CAB January 1990. The F-CAB was selected for the first simulation because it had a continuous display across three horizontal windows with a slight downward view on the left and right (fig. 11). The continuous view with some corner look-down provided adequate visual cuing for the fidelity assessment tasks, especially for the dash/quick-stop task. The cab had some limitations that were thought to be minor compared to the advantage of continuous visual presentation. First, the F-CAB could only be used with a fighter seat. The seat was cushioned and had a slight backward tilt. Although it was adjustable, the seat had limited movement. The full cushion also meant that the seat vibrator was muffled somewhat compared to the typical helicopter seat. Second, the display panel for flight instruments interfered with the cyclic controller. The display panel did not allow the use of the curved stem cyclic controller that is typical in the UH-60A. The curved section limited forward movement of the controller. A compromise was to make a straight and sectioned controller stem. The requirement for the UH-60A stick in the F-CAB was to have the same control travel forward and backward and to have the same grip location and arc on the stick. The small instrument panel did not lead to compromise because only a limited set of flight instruments was used for the simulation. The instruments were in the same location as they would be in the aircraft.

The N-CAB was used in the second simulation. The N-CAB is different from the F-CAB in two specific ways. First, the visual presentation is a four window display with three horizontal windows and a chin window (fig. 12). The scene is not continuous

across the horizon and appears as separate windows with wide black spaces between each window. Overall, the field of view (FOV) in the N-CAB is wider than the F-CAB (N-CAB horizontal coverage is 140 deg versus 120 deg in the F-CAB), but vertical coverage (50 deg) is the same (figs. 13 and 14). The second difference in cockpits was that the instrument panel structure was higher in the N-CAB, but due to redesign considerations the modified cyclic controller from F-CAB was used. In addition, the cushioned fighter-type seat was used because the seat shaker was designed for the seat.

Although the visual scene coverage in the simulator cabs differed, there was a greater difference in the FOV between the simulator and the aircraft. The hammer grid charts in figures 13–15 for the FOV of the F-CAB, N-CAB, and the aircraft show the differences. The aircraft FOV is much larger than either I-CAB, and the overhead view and most of the side view from the aircraft is not available in the simulator. For example, when the FOV from the F-CAB (fig. 13) is overlapped with the aircraft center window FOV (fig. 15), the coverage is limited to the center, lower-right, and lower-left portions of the aircraft FOV. On center, the aircraft has 10 deg more up-view and about 15–20 deg more down-view. The F-CAB right side down-view is about 10 deg wider than the aircraft but is also about 5 deg less in the downward direction. The left side of the FOV from the F-CAB shows about 10–15 deg more coverage than the aircraft in the down and left portion of the window. The aircraft chin window, right side window, and left side window FOV do not exist in the F-CAB. Similarly, the N-CAB FOV (fig. 14) is limited compared to the aircraft. The FOV from the center and right windows overlaps the FOV from the aircraft center window, but the center window on the N-CAB covers most of the left of center portion of the aircraft FOV, while the right window overlaps the right portion of the aircraft FOV. There is a gap in coverage of about 15 deg between the center and right windows in the N-CAB due to the spacing of the TV monitors. The gap is from the centerline (0 deg) to 15 deg right of the centerline (referenced to aircraft FOV). The lower right side window in the N-CAB overlaps the lower right portion of the aircraft center window FOV with slightly more coverage to the right than the aircraft. The aircraft has 10 deg more up-view across the FOV and 15 deg more down-view in the left hand portion of the center window. The left-most window in the N-CAB overlaps most the left side-view FOV from the aircraft except about 25–30 deg on the far

left portion. The aircraft FOV from the chin window, the right side window, and the overhead window does not exist in the N-CAB.

The cyclic and collective grips (figs. 16 and 17) were actual UH-60A grips. The functions on the stick were duplicated by the simulation. The communication switch, stick trim beep, and trim release switch were the same as the UH-60A. The only change was to use the Go-Around Enable switch as the Abort-Sim switch. The panel instruments were general purpose simulation instruments except for the Attitude Director Indicator (ADI), which was patterned after the UH-60A, and the radar altimeter instrument, which was similar to the UH-60 instrument. The strip gauges were not UH-60A-type indicators, but were used for the simulations because they were similar to UH-60A strip gages. Other instruments were refaced with paste-on gauge faces that were representative of the UH-60A instruments. The other difference was that the ADI turn and slip indicator could not be interfaced with simulation lab electronics and so a separate turn and slip indicator was at the lower left side of the ADI. Figure 18 shows the simulator instrument panel arrangement versus the aircraft.

The collective and cyclic sticks were interfaced with control loaders. The loaders used in the VMS were manufactured by McFadden Systems, Inc. They are a electrohydraulic force servo that can be programmed to produce realistic force-feel cues over a wide range of operating conditions (ref. 23). The controllers were interfaced with the simulation laboratory EAI 2000 analog computer for setup and force balance. In the simulation, the characteristics of the controllers during simulator flight were programmed through the Gen Hel UH-60A mathematical model through a digital interface. The setup, breakout, and force gradient for the controllers were patterned after reference 8 and adjusted for project pilot acceptance. The calibration curves are shown in figure 19. The force characteristics values set up for the force-feel system are shown in figure 20.

A seat shaker to provide vibration cues to the pilot was designed and installed in the simulator cockpit for the two simulations. The model for driving the seat shaker was obtained from Sikorsky Aircraft Company as part of the 1989 update contract. Previous simulations in the VMS have lacked this cue. The shaker provided the aircraft vibration cues and helped to mask the motion system noise and turn-around bump.

The seat shaker is driven with frequency and amplitude inputs. The frequency is nominally set at 17 Hz (the four-per-rev frequency for the UH-60A at 100 percent rotor speed) and a delta frequency (limited to 2 Hz) is calculated using a mathematical model that requires inputs of rotor speed, collective position, load factor, and airspeed. The amplitude of vibration is calculated using a simple algorithm:

$$A_{TOT} = K_F[K_{XC}(A_0 + \Delta A_{VEL} + \Delta A_{NR}) + K_{TL}\Delta A_{TL}]$$

where

A_{TOT}	total seat shaker amplitude (one-half peak-to-peak), g
K_F	overall tuning gain (nominally 1.0)
A_0	base amplitude at 50 percent collective in hover (= ± 0.1g)
ΔA_{VEL}	delta due to airspeed variation, g
ΔA_{NR}	delta due to rotor speed variation, g
K_{XC}	collective gain factor (function of collective stick position)
ΔA_{TL}	translational lift increment, g
K_{TL}	translational acceleration gain (proportional to aircraft acceleration)

The above values were obtained from a series of graphs that were empirically determined from a measured vibration data base. The resulting vibration changes with aircraft state. For example, increased vibration in the translational lift region of the rotor from hover to forward speed was favorably emulated in the simulation. During the simulator tests, the seat shaker amplitude was set at a lower value than was known to exist in the aircraft. This was done to reduce pilot fatigue, but for some maneuvers the reduced amplitude or gain may not have provided the necessary threshold for cuing thereby negating the desired effect.

Aural cuing was provided in the simulation by mixing component noises from the VMS Wavetek sound generator and a digital noise generator. The synthesized noise was designed to emulate the UH-60A. The primary source noise comes from one-per-rev and from the transmission. Engine noise from spool-up was also synthesized. The noise was piped into the cab speakers located behind the pilot seat. During the simulation the noise was adjusted to avoid pilot fatigue.

4.3.3 Vertical Motion Simulator (VMS)

The VMS has six degrees of freedom. The large motion system has a translation travel envelope of ± 30 ft vertical and ± 20 ft lateral (along beam) and ± 4 ft longitudinal (perpendicular to the beam). Operational limits are set lower using software limiters for safety and to avoid travel into mechanical stops. The cab was oriented for large lateral travel during both simulations. Figure 21 shows the VMS in a cutaway and includes a table showing system performance limits and nominal operational performance limits.

Aircraft motion in the real world cannot always be duplicated on the simulator. In simulations a compromise is made to give the pilot the proper high-frequency motion cuing, but duration and magnitude are generally less than experienced in real aircraft. The limits of motion cuing are dependent on the envelope of the physical system. The VMS is a large envelope system, but ultimately it is still limited by available travel distance and dynamic response. The motion system must be able to respond with proper onset cuing when the pilot changes state, but since the flight of an aircraft is not a single change of state, the hardware must be in a physical position to respond to a new commanded change. To accomplish this task, second order washout filters are primarily employed on the VMS. A synopsis of the logic used is contained in reference 24. A short description is quoted here: "The computed motions of the modeled aircraft cockpit are high-pass filtered, and sometimes directly attenuated, in order to be accommodated by the simulator motion system. . . . For reasons of simplicity and operational flexibility, the VMS constraint logic . . . is basically linear. Rotational and linear accelerations computed for the cockpit are modified for representation in the simulator by the following general relationship:

(simulator acceleration command)/(aircraft acceleration)
$$= Gs^2/(s^2 + 1.4\omega s + \omega^2)$$

Where ω is the characteristic frequency of the high pass filter, s is the Laplace operator, and G is the high frequency gain. . . . All the gains (the G terms) and the filter frequencies are readily accessible variables, and are set to optimize the motion "recovery" for the particular task being simulated."

A diagram showing motion constraint logic is shown in figure 22. In addition to this logic, safety features within the system are employed in case a commanded input exceeds the capability of the system. For example, a parabolic limiter is used to prevent the

system from running into displacement limits. "The parabolic limiter acts to command a maximum acceleration opposite to the direction of travel whenever the velocity and/or displacement is such that this maximum acceleration will stop the motion just short of a displacement limit" (ref. 23). Unfortunately, sometimes these limits can be sensed by the pilot—particularly if his level of aggression is high or if he encounters motion stops or experiences turnaround bump. Comments from the 1990 simulation indicate that for the dash/quick-stop task, there was an adverse motion cue during initial pitch down and acceleration that momentarily gave a reversed sensation before returning to acceptable motion cuing. This particular miscue was not sorted out or determined during the simulation period, but it was discovered on a subsequent simulation that an error existed in the process of calculating the compensation for a residual tilt variable (ref. 25).

Motion system setup values for gains and characteristic frequencies for the simulation experiments described here are given in figure 23.

4.3.4 Visual System

The image generator for both simulations was the DIG-1. It is limited in terms of object density, does not have the capability for micro texture, and the resolution is poor (ref. 26). These limitations have made it difficult for pilots to perform precision hover tasks in previous simulations with simple rate command systems. To alleviate some of these shortcomings, this simulation duplicated the hover boards on the visual data base. The replica (excluding fine texture) provided about the same visual information, since the combination of horizon and hover boards were the primary visual cues for the pilots during the flight tests. The Crows Landing Airfield runways and side ramp were represented on the data base and to compensate for the lack of ground texture in the scene, a series of checkerboard patterns were laid out (along the side ramp where the hover boards were located) to give ground reference and to provide velocity cuing. In addition, the crane structure with cables and boom which supported the hover boards was displayed, and other objects (cones and trucks) were placed in the scene to give some size cuing to the pilot. Figures 11 and 12 are examples of the scene content and general character of the display in the F-CAB and N-CAB.

5 FIDELITY ASSESSMENT

A piloted simulation involves the interconnected structure (through the host computer) of the mathematical model, simulator motion system cuing, image generation and presentation (cuing, resolution, detail, dynamics), and the interface cockpit (pilot station, controllers, displays, aural cuing, vibration cuing). This physical structure constitutes the simulated aircraft.

The process of fidelity assessment in this experiment as previously stated is: (1) Determine how well the simulated aircraft represents the actual aircraft (dynamically similar) and (2) Determine how well pilots perceive the simulated aircraft to represent the actual aircraft. The first part is done objectively by comparing the response of the individual components of the simulation to the appropriate aircraft response. The second part is done through a subjective evaluation of the simulated aircraft by trained test pilots. In addition, objective assessment of pilot performance (strategy, workload) from flight to simulator is used to help explain the perception of the pilots when possible.

The methods used for this experiment involve time history data, piloted frequency sweep data, and the power spectral density function. The time history recordings of the tasks performed in flight and in the simulator were transcribed from tape for selected input/response variables and were used for model verification as well as pilot strategy evaluations. The data for frequency response comparisons were generated by using the piloted frequency sweep method outlined in reference 27. The frequency sweeps were used to evaluate frequency response of the model versus the aircraft, and frequency response of the motion and visual systems versus the model. The power spectral density function was used for workload comparison.

Time history data comparisons for math model verification have been done extensively in the formulation of the model used in this experiment. Generally, dynamic checks of the model have been done by making step inputs into the controllers and recording a time history of the response for selected variables. A compilation of responses of simulation versus aircraft is contained in reference 13. Further comparisons will not be done here. Figure 24 is a sample of the type of data that is contained in the reference. Discussion in reference 13 indicates that the initial response of the model compares well with the flight data, although the simulation rates sometimes have less damping. Divergence shown after several seconds may be due to flight

data drifting from trim because of pilot difficulty in controlling the unaugmented aircraft (roll acceleration is not zero for the aircraft, although other data indicate that it is). There may also be some control input hysteresis in the flight test data. Other causes may be due to minor math model deficiencies due to compromises made to simplify modeling. In general, the simulation compares well with flight test data and the model fared well in ʾrevious simulations. To assure that the same model v ʾ used for each pilot session, the working model was ʾercised with a dynamic check routine automatically sequenced by the computer. Strip chart data generated by the routine were checked against a master set of data to verify the responses. Figure 25 shows a sample of this data for several daily checks that have been overlaid.

Frequency sweeps for this experiment were done for the hover condition, (stability augmentation system (SAS) on and FPS off) since the tasks were primarily done in the hover low-speed range. A frequency sweep is generated by the pilot for each controller by moving the controller in a sinusoidal fashion starting at very-low frequency (for 20 sec) and continuously sweeping while increasing the sweep frequency up to a predetermined maximum (about 3 Hz). The pilot is coached by a data observer to ensure good frequency content. The data record is about 100 sec long when the sweep is completed. In general, a series of three sweeps are done for each controller to assure good frequency coverage and good data recording. The most difficult axes to sweep are the lateral and longitudinal cyclic controllers because the aircraft (real or simulated) tends to gain speed and is displaced from hover at the long-cycle (low-frequency) sweep rate. The data from these axes usually span from hover to approximately 20+ knots. The pilot is allowed to correct for this drift as long as the correction remains relatively uncorrelated with the input signal. The data from the sweeps were processed using the CIFER (Comprehensive Identification from FrEquency Responses) utility (ref. 28). This utility contains several programs for the analysis of frequency response data. The subprogram FRESPID (Frequency RESPonse IDentification) was used to generate Bode plot information to compare the flight test and simulation. FRESPID allows the data to be concatenated. This feature allows the use of all sweeps for a given axis so that the widest possible frequency spectrum can be covered.

The objective assessment of pilot performance from generated data to determine the fidelity of the simulation is driven by the comments made by the pilots, because these comments give the pilots' perception of flight versus the simulator experience. Conversely, the pilots' perceived notion about lack of fidelity in an element of the simulation may not be the actual cause of lack of fidelity. To address these issues, the analysis concentrates on the pilots' strategy in performing a maneuver and on the fidelity of cuing in the simulation (motion, visual). The pilot strategy is pursued through a comparison of the time history data for a task from flight and simulation. The fidelity of visual/motion cuing is pursued by determining if a pilot input (frequency of input variable) to the visual/motion system occurs in a region of phase mismatch for visual and motion that may be critical to perceived fidelity. Finally, differences in piloting technique may show up as differences in workload. A workload analysis was performed on the data using the power spectral density function to compare stick activity as a reflection of workload from flight to simulator and to calculate a pilot cutoff frequency for each task. The application of the power spectral density to controller activity has been used in previous experiments to compare flight to simulator task performance (ref. 1, for example).

Although the interface cockpit is important to pilot perception of the simulated aircraft, no objective approach was used to check the fidelity of the controllers or gages. The assessment was done by relating pilot comments about the controllers, displays, aural cuing, and vibration. Initial setup was left unchanged and lack of "feel" in the controllers or incorrect noise was not pursued due to time limitations on the experiment.

5.1 Simulator Systems Fidelity

The determination of the dynamic similarity of the simulated aircraft to the actual aircraft is pursued in this section. To assess simulation fidelity objectively, is important to examine the fidelity of the individual components that constitute the simulator system. These individual systems are assessed as follows:

1. Documentation of the mathematical model versus the aircraft in terms of response/input from piloted frequency sweeps is used to assess the "goodness" of the mathematical model. Dynamic response is compared by overlaying Bode plots of the magnitude and phase relationships of the commanded variable (in this case an angular rate) to stick input.

2. The fidelity of the visual system is assessed first by evaluating the ability of the system to produce scene

content that emulates the real world, and second, using a piloted frequency sweep to compare visual system response to the math model. In addition, the delay introduced by the time sequence of events through the host computer is assessed and the effects of the delay reported.

3. The motion system response is compared with the math model using the piloted frequency sweep method to determine the dynamic response of the motion system to model command. Bode plots for the corresponding simulation motion variable (angular rate of motion as a follow-up to model command) to stick input, are overlaid with the mathematical model data to show the model/motion response relationship. The motion response curves include the effects of the washouts and system gain.

5.1.1 Mathematical Model and Aircraft Frequency Response Comparison

The dynamic response data comparing the mathematical model to the aircraft are shown in figures 26–29. The data were generated by a test pilot sweeping the lateral-cyclic, longitudinal-cyclic, collective, and pedals. The Bode plots obtained are for:

$$p/\delta_{lat}, q/\delta_{long}, h/\delta_{coll}, r/\delta_{ped}$$

Figure 26 shows the comparison of data from flight and the math model for the lateral axis (p/δ_{lat}). The agreement from 0.6 rad/sec to 10.0 rad/sec is fairly good for the magnitude and phase. The discrepancies in the data from flight to simulator in this range are small. Outside this range the data diverge. Data confidence outside the 0.6–10.0 rad/sec range are suspect due to low values for the coherence especially for the flight data (fig. 26, bottom plot). Generally, data with a low coherence function have less correlation of output to input (data with coherence value 0.8 and higher are considered high confidence data for this experiment). All in all, these data show a good representation of the lateral axis in the simulation.

Figure 27 shows data for the longitudinal axis (q/δ_{long}). This comparison shows some discrepancies between the math model and aircraft. The magnitude and phase are similar in character, but the phase plot shows differences approaching 70 deg. The coherence function plot shows that the flight data have poor coherence except for the range 2–7 rad/sec, but the math model coherence function is above 0.8 from 0.6 rad/sec and above. In the region of acceptable coherence value

the agreement between flight and the model is still not good, but the apparent poor quality of the flight data, except for a small region, makes the comparison difficult.

Figure 28 is a comparison of data for the collective axis (h/δ_{coll}). These data look very good, in general. However, when the coherence function is examined, the math model data exhibit poor coherence above 5 rad/sec thus making that region for the simulation data somewhat suspect. The good agreement, otherwise, suggests that the collective axis is well represented in the simulation.

Figure 29 shows the yaw axis data (r/δ_{ped}). This set of data shows good agreement between flight and the math model. The flight data exhibit low coherence values above 7 rad/sec, but, in general, the simulation demonstrates good agreement with the aircraft for the directional axis.

A more extensive analysis on comparison of math model frequency sweep data to the flight vehicle can be found in reference 19.

5.1.2 Visual System Fidelity

The computer generated visual presentation in the simulator cockpit is a facsimile of the real world. The pilots' perception of this scene determines to a large extent their ability to perform tasks in a satisfactory manner and to duplicate the strategy used on the aircraft. This section will discuss the interface of the DIG-1 visual system with the simulation and the artifacts of that installation on the simulation.

The physical installation of the monitors that present the computer generated scene to the pilot requires that the pilot's eyes be aligned to a point in space where, in theory, the scene is presented. This "eye point" is set up to give the visual computer a physical reference point for the computer generated scene. The pilots can align to this point by using an alignment structure in the simulator cab. They adjust the seat up, down, forward or back to reach alignment. The proper eye point location places the pilots' eyes at the optimum viewing location for the scene. The point is basically a 70th percentile point for all pilots. The nature of this arrangement means that all pilots have the same viewing point of the scene, but the pilots cannot look around corners to see more. They are, in effect, restricted to a fixed envelope of view and can change the view envelope only by rotating (phi, theta, psi), translating (vertical, lateral, longitudinal),

or tilting (combinations). They do this by moving the simulated aircraft through the scene. The main restriction then becomes their fixed position FOV at any point in time. The fixed FOVs for the F-CAB and N-CAB are shown in figures 11 and 12.

The DIG-1 is restricted in how much detail can be presented in a scene. This first generation machine is a line-priority-based system and is limited to approximately 1,500 total lines (lines are used to form polygons which are used to form surfaces). Object density is a function of the available lines. That is, the first 1,500 lines drawn are given priority in a scene; if more lines are required to construct a scene (panning back includes more scenery), then the priority of drawn lines dictates the display. As scene changes occur, lines may pop in and out as their priority is called. The popping is due to line overload and lines with lower priority are eliminated or replaced as required. To reduce this effect on special task areas in the scene, often structures such as the hover boards will be drawn as a target and are given highest priority in the scene. Finally, no capability exists for micro-texture in the scene. Since some ground reference is desirable, a repeating checkerboard pattern was laid out in the scene to provide a velocity reference, especially for the dash/quick-stop task.

Resolution, luminance (brightness), and contrast are contributing factors to the clarity of the scene presented in the simulator cockpit. Imagery resolution is a function of luminance and contrast. The ability to resolve an image from a specified distance is usually defined in terms of visual acuity or in terms of contrast threshold. Visual acuity is the reciprocal of the size of the smallest resolvable target in arc minutes. Contrast threshold is the ability to distinguish contrast in a very low contrast, relatively large target. The DIG-1 was investigated in reference 26 to quantify the resolution of the display. A U.S. Air Force tri-bar pattern display was used to measure visual acuity in terms of spatial frequency (cycles/milliradian (mrad)). The pattern image was programmed for display in the simulator cab visual system and several test subjects were exposed to the pattern at varying distances and at different contrast conditions (fog, no fog). The results showed that for distances from 100 to 300 feet and with highest contrast available (no fog), the visual acuity was about 6.0 arc-minutes/line (0.3 cycles/mrad) for horizontal resolution and about 4.5 arc-minutes/line (approx 0.4 cycles/mrad) for vertical resolution. When fog was introduced (lowering contrast) the visual

acuity got much worse (up to 9 arc-minutes/line at 300 ft). In a normal contrast outdoor daylight scene, 20/20 vision can usually distinguish 1 arc-minute/line. The fidelity assessment tasks for the UH-60A simulations were performed in the simulator with the pilot eye-point at about 100 ft stand-off distance from the hover boards and without fog so that the scene resolution was 4.5–6.0 arc-minutes/line. This resolution is tantamount to being nearsighted and images appear less distinct as distance increases. The less clear the image the more difficult it is to gauge the distance of the image, resulting in a lack of depth perception as the image becomes less clear. In addition, due to the projection medium in the simulator, the luminance at pilot eye-point in the simulator is far below an average outdoor daylight scene. This limits the contrast level that is achievable in the computer generated scene. The low light level also means that the pilots' eyes are more dilated to compensate for the low light level. Reference 29 suggests that visual performance varies both with pupil size and with scene illumination, resulting in a reduction in visual ability corresponding to the reduction in luminance. Inability to resolve the image may lead to other problems in the pilots' perception of the scene including their ability to detect small changes in spatial and angular position.

The DIG-1 is a 60/30 Hz system and has a pipeline structure where the process occurs sequentially. First, coordinate position information for a scene is transferred from the model calculations in the main frame computer to the DIG-1 visual computer. At this time, a scene for those coordinates is constructed and stored in a buffer and awaiting pickup for scene generation on the monitors. Finally, a scene is displayed. The first phase takes place in 33 msec, the second phase also takes 33 msec, and the third phase is an interlace at the screen which paints half the lines in 24.67 msec. The entire pipeline takes 91 msec for a scene to be displayed to the pilot in the simulator cab. This is often referred to as pure transport delay. This delay becomes part of the overall stick input to visual response in the simulator. Recognizing this, a compensation algorithm was developed by NASA to reduce the pure transport delay between model command and visual response. The final effect, analytically, is for the visual response and model response to be in phase over the frequency range of the simulation. The method used is based on a predictor/corrector tuned to a nominal frequency. Reference 30 gives details about this method.

13

The nature of simulation requires that several independent computers and systems be interfaced and information transferred from one system to another in a time-dependent frame. When the pilots move a control, they initiate a change of state. In simulation they have commanded a change to the force-feel system that feeds output to the math model which, in turn, sends information to the visual computer and the motion system. The clock time frame in which this happens depends on how the information is transferred. The delays present in this simulation series were analyzed by the simulation facility staff (ref. 31). Figure 30 shows the time paths taken by the signals going to the analog instruments and to the computer generated image display (CGI). A common signal path is followed from pilot input through the host computer and after conversion (multirate to non-multirate conversion time delay) a separate path is established for the CGI and the instruments. The CGI signal path includes a compensator (W5) in the computer for pure time delay (ref. 30) before exiting and then continues through pre-filters (W6, W7). Finally, the total pipe line delay for the CGI computation (W8) is accounted before image display in the cockpit. The signal on the analog path exits the computer and passes through pre-filters (W10, W3) with small delays before it is displayed at the instrument or strip chart. The analysis applied was reported in reference 32. The results from the analysis applied to the UH-60A simulation were stated: "Delays in this simulation were about 29 msec from pilot input to digital to analog output (analog path). These delays typically show up in analog instrumentation and on strip charts. Delays in this simulation from pilot input to scene presentation (CGI path) was about 19 msec for the DIG-1 CGI."

The visual system variables were not included in the final data set for the simulations. Figure 31 was taken from another experiment (ref. 25) performed after the UH-60A simulation. The figure illustrates the effect of the compensation algorithm used at Ames (ref. 30) to reduce the effect of pure transport delay from the computer generated image. Figure 31 shows that the algorithm is effective with the visual system (transfer function ϕ_c/δ_a), having almost identical response with the math model (transfer function ϕ/δ_a) so that when the motion response leads/lags the model response it is sensed as the motion leads/lags in the visual.

The bottom line for visual problems is that although there is compensation for the transport delay,
and there are compromises to increase object density, the DIG-1 is not satisfactory. The FOV is fixed in the simulator, the resolution/brightness/contrast cannot be improved, and there is little to no texture.

5.1.3 Mathematical Model/Visual-System/ Motion-System Frequency Response

The mathematical model was shown to have good dynamic response compared to the aircraft and the visual system response was shown to be almost identical to the model. The dynamic response of the motion system compared to the model is shown in this section.

The large mass of the VMS must respond on command to the pilots' change of state. When the pilots move a controller, they expect a response from the machine they are flying; in the simulator that response is delivered by the motion cue and visual confirmation. The cues the pilots receive must be in the sense expected for the action taken. The simulator hardware may not respond as desired. This may be due to the pilots' latency in the motion response (visual confirmation without expected motion) or they may sense movement without visual confirmation (lead of motion over visual). The literature suggests that in times of visual/motion distortion the pilot is apt to disregard the motion cue in favor of the more compelling visual reference cue (ref. 33). If for any reason the pilots get a visual cue first, then a motion confirmation later, or visa versa, they are apt to instinctively disregard the motion and/or put in a correction for the late/early motion cue. The correction may upset their position regulation and they will then have to make inputs, usually based on visual feedback, to regain or establish their target position. If there is mismatch in systems responses, sometimes the pilots feel that the aircraft is lightly damped or tends to have pilot-induced oscillation (PIO) tendencies, or, in the worst case, they get simulator sickness.

Perfect response of motion to mathematical model command would be for the motion and model responses to exactly overlay in magnitude and phase. The simulator motion displacement constraints do not allow this match. Also, the second order washout used on the VMS means that the motion response has phase lead over the model for very low frequencies, becoming almost coincidental in phase with the model over a range where the motion system is tuned to give

good phasing and acceptable gain. Then, at higher frequency, the motion response tends to lag the model (in phase) due to the motion servo dynamics.

Frequency sweep data from the 1990 simulation to establish the math model to motion response are presented in figures 32–35. The hover condition sweeps were done to produce the following Bode plot functions:

$$PB/\delta_{lat}, \ PSFU/\delta_{lat}, \ QB/\delta_{long}, \ QSFU/\delta_{long},$$
$$ALTD/\delta_{coll}, \ VZFU/\delta_{coll}, \ RB/\delta_{ped}, \ RSFU/\delta_{ped}$$

Figure 32 is the frequency response plot for PB/δ_{lat} and $PSFU/\delta_{lat}$. Where PB is math model roll rate in body axis (p), which is the commanded roll rate to the motion system, and PSFU is the motion system follow-up. The variable δ_{lat} is the lateral cyclic input. The plot shows that the phase curves intersect at about 2.5 rad/sec. For frequencies above this value the motion lags the model (in phase), and below 2.5 rad/sec the motion leads the model. The value used in the washout filters for gain (G) and characteristic frequency (ω) for the roll axis are G = 0.38 and ω = 0.70 rad/sec.

Figure 33 is the data for QB/δ_{long} and $QSFU/\delta_{long}$. The variable QB is the angular pitch rate command in body axis (q) from the model, and QSFU is the motion follow-up pitch rate. The variable δ_{long} is the longitudinal cyclic input. The phase data intersect at 2.2 rad/sec. At lower frequencies the motion leads the model and at frequencies above 2.2 rad/sec the motion lags the model. The values for G and ω are 0.50 and 0.70 rad/sec, respectively.

Figure 34 shows data for the vertical axis. The Bode plot shows data for $ALTD/\delta_{coll}$ and $VZFU/\delta_{coll}$. The variable ALTD is the rate of change of altitude ($\dot{h}$) and is the command variable from the model, and VZFU is the vertical velocity follow-up from the motion system. The quantity δ_{coll} is the collective stick input variable. The phase curves intersect at 1.0 rad/sec. The setup values are G = 0.80 and ω = 0.30 rad/sec.

Data for the yaw axis (RB/δ_{ped} and $RSFU/\delta_{ped}$) are shown in figure 35. RB is the angular yaw rate (r) in body axis, which is the command yaw rate from the model, and RSFU is the motion system follow-up yaw rate. The quantity δ_{ped} is the pedal input. The phase curves intersect at 2.5 rad/sec. The setup values were G = 0.50 and ω = 0.50 rad/sec.

In summary, the relationship of simulator motion response to mathematical model commanded input

through the controllers shows that there are only limited regions where the phase is coincident. The regions above and below these regions generally show increasing phase distortion, which, if encountered by a pilot while performing a tasks in the simulator, may lead to a perception of poor fidelity. Although the emphasis has been placed on phase difference as a measure of fidelity for the motion system, the reduced gain in the simulator in order to remain within the simulator travel envelope is a compromise from the actual aircraft. The effect of this reduced gain on pilot perception has only been addressed in this experiment by designing less aggressive tasks to reduce excursions to limits in the simulator. The onset acceleration is about 80 percent of aircraft acceleration in the vertical and lateral translational axes and about 40 percent in the longitudinal translational axis (only ±5 ft movement available). The pitch and yaw are gained at 50 percent and roll is gained at 38 percent. These values were set up using a standard practice in the VMS to get reasonable acceleration and rate cuing without jerkiness and to provide onset motion cuing consistent with the aircraft. A small amount of data addressing gained down-motion effects is contained in reference 25.

5.2 Pilot Evaluation—Perceptual Fidelity

Pilot evaluation of tasks performed in-flight and in the simulator was done using the Cooper–Harper handling qualities rating (HQR) scale developed in reference 6. The Cooper–Harper HQR scale (fig. 3) is basically a metric that measures the compensation required by the pilot to perform a task to a specified level of performance. A decision tree is used to narrow the assigned HQR value. Each rating is accompanied by comments from the pilot that justify the rating and detail his perception of work load and characteristics of aircraft systems. His comments relate whether aircraft characteristics enhanced or were detrimental to his performance.

Five pilots participated in the experiments in 1989 and 1990. Four pilots flew in the 1989 flight test and simulation. Three of the four pilots from the 1989 test returned for the 1990 simulation. Only two of the pilots were able to participate in the evaluation since the third pilot was called for other duty. A new pilot was added for the 1990 simulation and although he had not flown the flight test series, he was current in the UH-60A helicopter. Figure 36 summarizes the experience level

of the pilots who participated in the 1989 and 1990 experiments.

The sections that follow give the HQR values and comments for the tasks performed in flight and in the simulator. Comments made by the pilots concerning the simulated aircraft are also discussed.

5.2.1 Handling Qualities Ratings (HQR)

The HQR assigned by the test pilots for the flight tasks are discussed in this section. Data for the flight tests and the simulations are presented in figures 37–40. Figure 37 shows the HQR values given for the flight test. Note that the ratings are all in Level 1 (≤ 3.5) except for a single rating that falls into Level 2 (for the dash/quick-stop). The bob-up and side-step ratings show a spread of one rating point between pilots from HQR 2 to HQR 3. The dash/quick-stop task also has a spread of one point, although three of the pilots are near HQR 3 in Level 1, while one pilot has crossed into Level 2 with a HQR of 4. Altogether the ratings are fairly compact. Figure 38 shows the comparison between the flight test results and the 1989 simulation. The data are from a back-to-back comparison where a morning flight test was followed by an afternoon simulator session. The HQR values for the bob-up and the side-step maneuvers are slightly higher in the simulation than they are in the flight for the same pilot; however, the difference is only significant for Pilot 4 who has a 1.5 point rating difference for the bob-up and a 2 point rating difference for the side step. Pilot 4 rated the dash/quick-stop task the same in flight and in the simulator. The other pilots rated the simulator the same as the flight test or showed only a difference of one rating point or less. Figure 39 is a comparison of data from the 1990 simulation and the flight test. The 1990 simulation was run six months after the flight test so the flight test experience was not fresh. In addition, Pilots 1 and 3 did not take part in the 1990 simulation. The data show a slightly larger spread for Pilot 2 (triangles) with the simulation data for the bob-up and the side-step tasks moving into Level 2 (from HQR = 3 in the flight test to HQR = 4 in the simulator), but the dash/quick-stop HQR improved slightly to Level 1 for the simulator. Pilot 4 did not change his ratings for the bob-up or side step in the simulator from 1989, but increased his rating for the dash/quick-stop by one rating point to HQR = 4 for the 1990 simulation. Pilot 5 (bow tie) was a substitute for Pilot 3. Pilot 5 did not take part in the flight test in the summer of 1989

and had little simulator experience. Pilot 5 gave worse (higher) ratings than the other pilots for the bob-up and dash/quick-stop maneuvers, but his rating for the side-step maneuver is better than the other pilots in the 1990 simulation. Figure 40 compares the HQR values from the two simulations. The ratings are reasonably compact, except for the ratings given by Pilot 5 on the bob-up and dash/quick-stop maneuvers. These ratings can be put into perspective by summarizing the pilot comments (given below) on their HQR values for the tasks. The comments are excerpts from the complete comments from transcripts, the questionnaire, and reference 34 to get specific comments from the pilots. Complete comments from the test tape transcripts from flight and simulation are given in appendix B.

Comments for bob-up task: Flight—The flight task was easy because: (1) The hover-board target was a good cue, especially with the ladder up (2-ft stripes on the support structure between the boards) on assent since the upper hover board was not in view at the lower hover position. Hover targets were crisp and detailed and, except for longitudinal cuing, gave good feedback on spatial position. (2) There was precise heave control and there were no overshoot problems. The airplane tends to go straight up. (3) There was precise heading control. **Simulator**—The comments are applicable to both the F-CAB and the N-CAB cockpits. The bob-up task was slightly more difficult in the simulator because: (1) There was poor vertical and horizontal FOV in the simulator with no view of the upper hover board target when at lower hover position. (2) There was image blurring in the CGI during ascent and descent and, in general, the image was less crisp in the simulator. (3) There was no ground rush on descent. (4) The heave axis appeared to be lightly damped and there was a tendency to get PIO. (5) Aural feedback of the engine and drive train noise was poor. Longitudinal drift was difficult to pick up from the hover boards in both the flight test and in the simulator. Although difficulties existed in simulation, the overall control strategy was the same from aircraft to simulator.

Comments for dash/quick-stop task: Flight—The task was difficult in the aircraft because of restriction on the nose-down attitude to start the dash. It was hard to hold 20 deg nose down because the aircraft tended to go more nose down. More than 20 deg down resulted in the loss of FOV because the instrument panel blocked the horizon. There was also loss of FOV on the quick stop if the nose up was more

than 20-25 deg. It was difficult to keep from ballooning above maximum altitude criteria on the quick stop. Two pilots reported wing roll reversals during the quick stop with the sensation of sliding in the roll direction. Ground rush was an important cue during the quick stop portion of the maneuver. **Simulator**—It was more difficult to perform the dash/quick-stop in the simulator because: (1) FOV, lack of texture, and some image blurring during acceleration/deceleration caused loss of depth perception and forced a greater reliance on the radar altimeter because of lack of confidence in height cues. (2) FOV limited the initiation of the maneuver to -15 deg nose down rather than the 20 deg in the aircraft. (3) The simulation appeared to require more collective input to establish hover at end of deceleration. (4) A false motion cue on pitch down during acceleration seemed to first go back then forward (a later simulation determined that the washout for residual tilt had been set incorrectly (ref. 25)). A modification of pilot strategy as a result of experience in the simulator made it possible to perform the maneuver with minimal pilot compensation; however, the strategy heavily relied on the radar altimeter for both height cuing and pitch cuing, thus eliminating a purely visual dash/quick-stop maneuver.

Comments for side step task: The side-step maneuver was equally difficult in flight and in the simulator primarily because of the spacing between hover board targets. Aggressive side steps were difficult to perform because stabilization at the end of the step became more difficult as the roll-reversal angle increased. **Flight**—Crisp inputs were made to initiate a side step with 15-17 deg of roll attitude change from trim. The roll reversals were made smoothly, but were generally taken out more slowly as the pilot anticipated the stop point at the far target to the hover point. The roll attitude damped quickly with little or no overshoot and no PIO tendencies. The maneuver was, for the most part, easy and predictable, but there was more activity on the pitch cyclic and yaw axis to establish hover than was deemed comfortable by some of the pilots. The hover targets were crisp and detailed with good small-angle feedback, but longitudinal drift was still hard to pick up. The noises from the engine and drive train were helpful cues during the maneuver. **Simulator**—Roll damping and heave damping appeared to be lighter than in the aircraft. Heave motion cues appear marginal. Anticipation of the stopping point at the far hover target was difficult in the simulator due to limited FOV and this made the task

less predictable than in the aircraft. Targets did not appear to be as crisp in the simulator as they did in flight, and there was a lack of depth perception. Angular changes in the simulator did not appear to be as large as those used in the aircraft. Pilot 4 had difficultly stabilizing the hover position at the end of the task. He had to make small corrections almost constantly and sometimes felt that his corrections went in the opposite direction than he intended (a white pointer to show the aircraft nose position was superimposed in the computer generated image; the pilot may have concentrated on stabilizing the pointer in the scene and with the lack of depth perception, may have been confused about which mode (lateral or yaw) was initially oscillating).

A method for predicting pilot HQR assignment for tasks performed in flight and in the simulator was developed by researchers from the University of California at Davis using data from this experiment. The method uses structural models of the human pilot (refs. 35-39) with input data from from flight and the simulator to obtain a pilot crossover frequency which was used to derive a handling qualities sensitivity function (HQSF). The HQSFs from the flight and simulator are compared to show the relative performance of a task and the value of the HQSF is used to predict the HQR level that would be assigned to the task. The results for these experiments are reported in reference 40.

5.2.2 Discussion of Pilot Comments

The comments by the pilots concerning their experience in performing the fidelity assessment tasks in flight and in the simulator gives clues to investigate causes for lack of fidelity in the simulator compared to flight. Three areas have been singled out by the pilots for comment: (1) lack of vehicle damping in the simulator compared to the aircraft, (2) lack of visual cuing in the simulator that is comparable to the real world including FOV, (3) motion cuing in the simulator is sometimes marginal. The analysis will concentrate on these areas to evaluate the fidelity of the simulation. The comments relating to the bob-up task and the side step, in particular, are probably more important in separating simulator work load from aircraft work load because the hover board targets were duplicated on the simulator visual data base. The pilots used the targets almost exclusively when performing the tasks in flight and in the simulator, so differences in perceived performance between flight and simulator can be addressed

more directly. For example, the tasks performed before the hover boards are basically tracking tasks in the sense that the pilots are trying to regulate a position on the hover board at the start. Completion of the maneuver in this type of task allows the use of pilot model techniques. On the other hand, the dash/quick-stop task was a more open-ended task because, although the task was performed in the simulator over a good .epresentation of the Crows Landing airfield, without the ability to duplicate the ground textures for ground rush cue in the simulator, the total visual effect was different. The radar altimeter became more important than the visual scene and the dash/quick-stop became an inside to outside task in the simulator. This task is more difficult to analyze with confidence.

Visual/motion cuing in the simulator was addressed by Bray in reference 24. He discusses the effects of lack of scene detail and motion cuing deficiencies on the pilots' ability to perform tasks in the simulator compared to in the aircraft. He further discusses the fact that pilot comment is especially sensitive to visual/motion cuing deficiencies, but tempers that by saying that pilot opinion has not been particularly helpful in identifying sources of cue deficiencies. To this end, it becomes necessary to apply an analysis that is more objective in the determination of simulation deficiencies that cause a lack of fidelity. The analysis depends not only on pilot HQR values and comments, but addresses the issue of pilot work load, simulator motion fidelity, effects of time delay, and mathematical model validity. Pilot comments from appendix B will be used to place emphasis when it is deemed appropriate and to verify pilot reaction to a particular discovery of degraded fidelity. The first part of this approach is to examine pilot comments regarding the visual reference in the simulator versus flight.

5.2.3 Comments on Visual Cues

Pilot comment on visual reference in the simulator was concerned with FOV, clarity of images and lack of depth perception, and lack of texture. Although it is not possible to determine the effect of each of these items on the work load performance of the pilots in the simulator, the comments can be used to address the effects that the pilots perceive from the image on their ability to perform a task.

Field-of-view (FOV)– The simulator cab FOV was a limiting factor on the pilots' ability to perform the tasks as they did in the aircraft. This limitation was apparent for all the fidelity assessment tasks in both the F-CAB and the N-CAB. The bob-up and the side-step tasks were affected by the pilot's inability to adequately lead the stopping points for establishing stabilized hover positions at the end points of the tasks. In the bob-up the pilot could not see or anticipate the upper hover target, and in the bob-down could not see or anticipate the lower hover target. This led to overshooting the targets and increased activity to establish a stabilized hover at the hover targets. The controller inputs to stop on the targets were more abrupt and sometimes upset the stabilized flight. The FOV in the simulator was a major problem for the dash/quick-stop task. The references for spatial position virtually disappeared in the pitch down for acceleration in the dash and completely disappeared during the pitch up to begin the quick-stop. This lack of visual reference during the task led to an altered strategy in the simulator where the pilots relied more on the radar altimeter for height reference than on the scene and checked with the scene only for final confirmation of hover at the end of the task.

Lack of depth perception– Image clarity is a contributing factor to the lack of depth perception. This issue relates to the general evaluation of a computer-generated visual in terms of the viewer's ability to resolve imagery. The resolution in the simulator was poor (4.5–6.0 arc-minutes/line or 0.4–0.3 cycles/mrad) and luminance and contrast were low. The inability to resolve small angular changes from small translational changes was a result of lack of depth perception in the simulator visual scene. Spatial position is difficult to maintain without good visual feedback.

Texture– The DIG-1 does not have the ability to produce micro-texture patterns to emulate ground texture or other textured surfaces. The lack of texture eliminated some important clues for the pilot. Pilots commented on their inability to detect small movement over the ground, and they had difficulty gauging their height above the ground. They did not experience ground rush on the bob-down task or ground rush at the end of the quick-stop task. These cues were present in the aircraft during the flight test and gave them a sense of spatial position as well as the sensation of closure rate to the ground surface. The lack of texture was partially compensated for by a repeating

checker board pattern in the simulator, but for near-ground tasks was not as desirable as micro-texture.

The visual display limitation effect on pilot HQRs is difficult to quantify. The lack of visual information definitely altered the performance of the dash/quick-stop task in the simulator, but the pilots commented that the bob-up and side-step tasks were performed in the simulator as they were in the aircraft. The investigation of the simulation fidelity is continued by looking at the time history data from the flight test and from the simulator.

5.3 Pilot Performance/Strategy—Time History Data Comparison

Time history data provides the opportunity to see the activity generated by the pilot and to observe any differences between flight and simulation for a particular task. The data may not answer questions concerning lack of fidelity, but it may point in a direction to pursue a solution. Time history data are only available for the the flight test and for the 1990 simulation. Although five pilots participated in the experiment, Pilot 1 and Pilot 3 did not participate in the 1990 simulation, and Pilot 5 did not participate in the 1989 flight test. A comparison of flight to simulator data, therefore, can only be made for Pilot 2 and Pilot 4. Data are limited to tasks with the FPS off.

The bob-up task will be addressed first, then the side-step and the dash/quick-stop tasks. To simplify the comparison, a typical time history for a maneuver has been selected from flight and from the simulator and overlaid. Only a single variable versus time is used to represent the task. The bob-up task is represented by the change in altitude versus time, the side-step task by roll attitude versus time, and the dash/quick-stop task by pitch attitude versus time. A limited data set has been selected to illustrate the activity in maintaining spatial position during the tasks (i.e., controller position, pitch, roll, yaw, and altitude) and to show the rate of change of these data. In addition, the time history data for selected rate variables are used to investigate the frequency of input to the motion system from the simulated model. These data are used to determine if those input fall in frequency regions where model/motion phase distortion exceeds acceptable levels for high fidelity motion cuing. A more extensive set of time history data (selected variables only) for the tasks in the experiment (simulator and/or flight) is shown for each pilot in appendix C.

5.3.1 Bob-Up Time History Data

The flight and simulator bob-up task for Pilot 2 is compared in figure 41. Figure 41(a) compares bob-up/bob-down altitude for the task. The flight maneuver (solid line) is started from a steady hover at the lower hover board. The pilot pulls collective and rapidly ascends toward the upper board. At about 20 ft from the upper board (about 2 sec from the top), the pilot begins to slow the rate of assent and eases to a stop at the upper board with little or no overshoot. Once in position, he regulates with only small corrections. The hover at the upper board is steady and maintained with little or no altitude change for about 8 sec and then the bob-down portion of the task is started. The bob-down is rapid, but as the pilot begins closing in on the lower board he again eases into the hover position with little or no overshoot. The final 20 sec hover at the bottom board is steady with only small adjustments to maintain altitude. Throughout the task, roll attitude variation is about ± 2.5 deg, pitch attitude variation is about the same, and longitudinal excursions are within 5 ft (figs. 41(b)–(c)).

The maneuver performed in the simulator (dashed line fig. 41(a)) is somewhat different. The initial hover is steady, and the bob-up is initiated with a rapid and aggressive collective input for assent as in the flight case, but the pilot does not ease off and there is no change in rate as the upper board is reached. Instead of easing into a hover, the pilot actually overshoots the upper board (approximately 2–3 ft) and must adjust the height down to acquire the board and hover. This height adjustment is not smooth and the adjustment becomes oscillatory throughout the hover and affects pitch and roll attitude. The time at the top board exceeds 10 sec before bob-down is commenced. The bob-down is rapid (steeper than the flight case), and again the pilot does not ease into the hover at the lower board, thus overshooting the target. The overshoot at the bottom board requires adjustment with resulting oscillation during the 20 sec hover. The corrections required in roll and pitch attitude for stabilization were more rapid (approximately 2.5 rad/sec) in roll with amplitude of approximately ± 2–2.5 deg and less rapid in pitch with lower amplitude change on the order of ± 1.5 deg. Heading was held within the limits of ± 5 deg (figs. 41(d)–(e)). Longitudinal drift was small with a slight tendency to drift away from the hover boards on the bob-up (about 2 ft) and then toward the hover board (approximately 3 ft) at the top board hover

19

position and during bob-down the drift increased to about 5 ft toward the board. Correction back to nominal position was done during hover at the bottom target.

The results for Pilot 4 for both flight and simulator are similar and are shown in figures 42(a)–(e). The flight data for altitude change (solid line in fig. 42(a)) show that Pilot 4 makes a rapid ascent at the start of the bob-up, but backs off and eases into the target altitude. Once on altitude, the pilot holds steady with little change in position. The top altitude is maintained for 8 sec before bob-down is started. The bob-down is steady and done in approximately 4 sec from top to bottom. Pilot 4 eases into position on the bottom target without overshoot. During the task, the roll attitude variation is rapid, but within ±2.5 deg (figs. 42(b) and 42(c)). The pitch attitude variation is small except for one large correction at the end of bob-down (up to an 8 deg change), but steadies out to less than ±2 deg during the hover. The longitudinal drift varies. The pilot drifts away from the board about 2 ft when in the bob-up then drifts toward the board during hover at the top (about 3 ft) and then drifts away from the board in the bob-down (about 14 ft total drift) 10 ft farther than target standoff distance before adjusting to the nominal distance during hover.

The simulator data (dashed line, fig. 42(a)) show that Pilot 4 makes an aggressive bob-up to reach the top hover position and overshoots the target about 3 ft. He puts in a correction with collective and undershoots, then continues with corrections while maintaining the top hover position. On the bob-down, he overshoots the lower hover position by 2–3 ft and rapidly corrects to the lower hover height. This pilot remains active on maintenance of pitch and roll attitude throughout the task. The pilot's roll attitude changes are rapid (about 2.5 rad/sec), but within ±2.5 deg of trim (figs. 42(d)–(e)) and heading is maintained within the desired ±5 deg. Longitudinal drift is within 4 ft throughout the task. Figure 43 summarizes the maximum, minimum, mean, and standard deviation for the data from flight and simulator used in the comparisons.

Flight to simulator comparison– The task was different in perception from flight to simulator. In the aircraft, the pilots tended to pull collective for rapid ascent, but then eased off as they approached the upper hover position. They were leading the stop at the top because they could see the top of the board early on and could anticipate when they should decrease

their vertical velocity to avoid overshooting the upper board. The bob-down was performed in a similar fashion. They had reasonably steady hovers at the top and bottom hover board targets. The pilots made more aggressive bob-ups in the simulator than in flight and as a consequence had to deal with simulator restrictions. In the simulator, the FOV was restricted and the upper board did not come into view until much later in the ascent; this takes away the anticipation of the stop point, thereby causing an abrupt stop when the top board comes into view. This abrupt stop in the simulator meant that the pilot put in a larger more squared-off input into collective to arrest his ascent. Because of the lateness of the input, the pilot overshoots the upper board and has to make additional adjustments to correct for the overshoot and, consequently, works more in the other axes to establish and maintain hover position. The situation was similar for the bob-down portion of the task. Overshoot and residual oscillation made the task workload higher in the simulator. Both pilots complained that the simulated aircraft was lightly dampened and prone to PIO. The pilots, however, did not seem to back off the aggressive approach for the remaining runs.

5.3.2 Side-Step Time History Data

The side-step maneuver was the other maneuver performed against the hover boards. The boards were set in a horizontal position with the targets 40 ft apart. The side steps in the flight test were done singly in each direction, but due to time constraints in the test schedule, the simulator side-step maneuvers were performed as doublets. There is similarity, however, since the doublets in the simulator were done to one side first with a 20-sec pause in hover position before stepping to the other side. Data will be compared for single side-steps left to right and right to left. Another factor in the performance of the task was the time allowed to traverse from side to side. The 7-sec time limit made the task moderately aggressive in the simulator. Although it was found that the task could be done more aggressively in the aircraft, the reduction in time from board to board resulted in increased workload to stabilize the end point hover, and resulted in worse HQR values. The discussion below is for the task performed with the 7-sec time limit in both the flight test and simulator. Note here that trim attitude for this configuration of the UH-60A aircraft was approximately 3 deg left wing down and approximately 7.5 deg nose

up. The trim attitude in the simulator was 3 deg left wing down and 4.0 deg nose up. This discrepancy was due to adjustments done for FOV considerations in the simulator.

Comparison of side-step maneuvers– Figures 44(a)–(f) show data for the side-step maneuvers as performed by Pilot 2. Figure 44(a) shows a comparison of a typical side step from the left to right as performed in flight and in the simulator. In the flight test (solid line), the initial roll bank angle reaches approximately +16 deg (right wing down, approximately 19 deg from trim). The roll reversal is almost immediate to an attitude of –25 deg (left wing down, 22 deg from trim), in about 2.5 sec. After the roll reversal, as the opposite target is approached, Pilot 2 is deliberate in trimming out to hover (–3 deg left wing down). The trace shows a stepping down to trim attitude as the pilot eases into the hover position after the quick stop. The roll attitude dampens quickly and there is no overshoot. Yaw rate adjustment was within ±3 deg/sec; pitch attitude dipped about 3 deg with the initial bank over and then during roll reversal the attitude pitched up about 3 deg (6 deg change) and back to trim after several small oscillations (figs. 44(b)–(c)). Longitudinal drift was within 5 ft throughout the maneuver. The trace for the left-to-right side step in the simulator (dashed line) shows that Pilot 2 made a crisper maneuver in the simulator with little or no hesitation in the roll reversal. The initial bank angle is much larger than the flight angle (+24 deg versus +16 deg) and when the roll reversal is completed, the attitude is approximately –33 deg (30 deg from trim) for quick stopping on the target. This angle is taken out quickly (no stepping) and there is an overshoot (approximately 5 deg) of the trim position and the resulting correction back to trim attitude shows several oscillations before it dampens. Pilot 2 was much more aggressive in the simulator than in the aircraft. The traces from the simulator for pitch and yaw adjustments show similar activity to the flight case (figs. 44(d)–(e)). Yaw remained within ±5 deg of trim, and pitch attitude reflected the changes noted for flight with a slightly lower magnitude change.

Data for the right-to-left side steps are shown in figure 44(f). The comparison has a similar character to the data shown for the right-to-left step. The level of aggression is higher in the simulator and there is overshoot of trim in the simulator, but not in the aircraft. Data for other axes were similar to the left-to-right side step case and will not be shown here (see appendix C).

Data for the side steps performed by Pilot 4 are shown in figures 45(a)–(f). Figure 45(a) shows overlaid traces from flight and simulator for the left-to-right side step. Pilot 4 performs the side step in flight (solid line) with an initial bank angle to +14 deg and does a smooth roll reversal to approximately –16 deg (13 deg from trim) for a quick stop and then trims the aircraft back to the hover. The pilot approaches the trim gradually and overshoots about 4 deg, then makes one large correction to get back to trim (about 5 deg) with several small oscillations occurring as the roll attitude dampens. Correction in yaw is less than ±2 deg/sec yaw rate and less than ±3 deg for pitch attitude with slight oscillation continuing throughout hover (figs. 45(b)–(c)). The left-to-right side step performed by Pilot 4 in the simulator (dashed line, fig. 45(a)) is slightly different. The initial bank is about 12.5 deg with the roll reversal (done more quickly than in flight) to a roll attitude of –18 deg for a quick stop before re-trimming. There is a overshoot of trim in the simulator, but on correction, there is an overshoot in the opposite direction and additional corrections are necessary to establish trim attitude. There are about three cycles of adjustments before the roll attitude dampens. During the course of these corrections, Pilot 4 complained of a lightly damped aircraft and PIO tendency. Yaw and pitch corrections are shown in figures 45(d)–(e). Yaw attitude drifted about 10 deg during roll reversal, but otherwise was within ±5 deg of trim. Pitch attitude went up 1 deg on the initial bank over, down about 3 deg during roll reversal, then up about 6 deg at the quick stop and back to trim with several small oscillations. The comparison for the right-to-left side step for Pilot 4 is shown in figure 45(f). The pattern of activity is similar to that experienced in the left-to-right step. Off-axes data are contained in appendix C. Figure 46 shows a summary of maximum, minimum, average, and standard deviation for the attitudes and angular rate data for flight and simulator for Pilot 2 and Pilot 4.

Flight/simulator comparison– Side-step maneuvers done in the aircraft were done with a fairly crisp input to initiate the side-step with between 15–17 deg of roll attitude change from trim. The roll reversals to quick stop on the target were usually made smoothly, but were generally taken out more slowly as the pilot tried to establish the hover trim position. The roll attitude seemed to dampen quickly with very small corrections to maintain altitude and position in the hover. Pitch attitude adjustment was active due to up and

down nose attitude during bank over and lateral quick stop with several oscillations occurring throughout the hover stabilization at the end of the task. Pedal activity was also oscillatory after the lateral quick stop. The yaw rates after the roll reversal were on the order of 2–3 deg/sec.

Side-step maneuvers done in the simulator had a slightly different characteristic than in the flight test. The two pilots who flew in the flight test and simulator used crisper inputs to initiate the rollover in the simulator than they did in the aircraft. The roll reversal to quick stop was equally crisp without stepping. Pilot 2 made much larger roll angle changes in the simulator than in the aircraft. Pilot 2 also experienced good roll subsidence when the lateral quick stop was completed, established a stabilized hover, and did not oscillate in the pitch axis. On the other hand, Pilot 4 seemed to have more trouble stabilizing a hover in the simulator than in the flight test. Pilot 4 experienced oscillations in roll, pitch, yaw, and heave to a much greater extent than did Pilot 2. The reason for the crisp control activity to stop the lateral translation may be due to the inability to see the target stop point early enough to initiate a predictable stopping point. Both pilots complained of a lightly dampened aircraft when trying to stabilize in hover after the roll reversal.

5.3.3 Dash/Quick-Stop Time History Data

The dash/quick-stop maneuver was an open-ended maneuver. The objective was to simply make a dash from a referenced hover position to a velocity of 60 knots and immediately initiate a quick stop back to a hover position. The quick stop was to be done as a rotation about the tail wheel while trying to maintain a reference altitude without excessive ballooning on the stop. The total length of dash to quick stop was about 1000 ft. The task was set up in the flight test to be a visual task with primary reference to the spatial position of the helicopter. One restriction imposed on the task was to keep the initial pitch within 20 deg because the simulator FOV would not accommodate a higher pitch angle and still have reference objects in the scene. This restriction was necessary to preserve the necessity for a visual, spatial task in the simulator. Also, the task was set up so that the pilot could use the hover board crane as a reference for the quick stop, both as a stopping point and as a object in the FOV when the task would be done in the simulator. The most difficult part of the task was thought

to be the need to stabilize all axes in the hover at the end of the quick-stop portion of the maneuver, thus spatial reference cues were necessary. Experience in performing the task showed that the flight test maneuver was done with an awareness of spatial position and the cues included subtleties such as ground rush and power management. These flight test references disappeared in the simulator. After several practice runs in the flight test it was decided, for repeatability, that the co-pilot would call out velocity in 5-knot increments starting at 40 knots so that the pilot could initiate the quick stop pitch reversal at about 55 knots (velocity drifted up about 5 knots as pitch reversal took place). This procedure was followed in the simulator with the test engineer calling the velocity change from the control room. The comparison of data for the flight test and simulator is given below.

Comparison of dash/quick-stop maneuvers— Typical dash/quick-stop tasks (represented by the pitch attitude) done by Pilot 2 in flight and in the simulator are overlaid in figure 47(a). The flight task (solid line) shows that the pilot initiated the dash with a pitch down attitude of approximately −15 deg (22 deg from trim) and modulated pitch attitude around −15 deg until reaching approximately 55 knots where the pilot began a pitch reversal to quick stop and establish a hover. The pitch reversal goes from −15 deg nose down to approximately +25 deg nose up (40 deg change). The pilot modulates the pitch around +25 deg attitude to bleed-off forward velocity to the hover position, then releases pitch back to the trim attitude for hover. The pilot eases back to hover trim with no overshoot and the pitch attitude dampens quickly. Roll and yaw attitude adjustments and altitude maintenance are shown in figures 47(b)–47(c). Yaw rate is about 2 deg/sec during the dash, and is slightly higher during quick stop before settling to about 1.5–2 deg/sec in hover. Roll attitude adjustments are small during the dash (less than ±1 deg), then roll attitude goes slightly right wing down (+3 deg attitude) during the pitch reversal, then gradually (in several steps) rolls left wing down (−5 deg attitude) in the quick stop. At the end of the quick stop, the pilot re-trims the roll back to hover trim (−3 deg attitude). In other runs, Pilot 2 experienced a roll reversal from right wing down to left wing down at the end of the quick stop, but it was quickly recovered to trim before hover was stabilized. Altitude increased in the dash from 25 ft to about 40 ft, remained there through pitch reversal for the quick stop,

22

then was gradually decreased to trim altitude (25 ft) as velocity was brought to zero for the hover. Trim altitude was maintained with a slight ±2 ft oscillation throughout hover. The length of the dash/quick-stop was 1200 ft.

The dash/quick-stop in the simulator (dashed line, fig. 47(a)) is somewhat different in character. Pilot 2 initiates the dash with a nose down attitude of approximately 28 deg (32 deg from trim) and holds pitch down at the same attitude until about 55 knots then begins the pitch reversal. The pitch reversal is from 28 deg nose down to approximately 25 deg nose up (53 deg change). The pilot holds the nose up attitude (with slight modulation) at +25 deg until the forward velocity bleeds to zero and then releases to re-trim the aircraft for hover. Roll attitude and yaw attitude adjustments are shown in figures 47(d) and 47(e). Roll attitude adjustments were small during the dash, but at quick stop there is a roll right wing down to about +10 deg attitude and a quick roll reversal to left wing down to trim (−3 deg attitude) with small oscillation (±1 deg) occurring throughout hover. This roll reversal was much more pronounced than for the aircraft experience. Yaw was modulated during the run from +5 to −5 deg attitude. Altitude increased during the dash and pitch reversal from 25 to 50 ft; decreased momentarily during a modulation of nose-up attitude, bumped up as pitch attitude was increased slightly, then dropped to 25 ft and settled out at about 30 ft (5 ft above original trim hover). The length of the dash was 1000 ft. Pilot 2 tried to duplicate the the cyclic activity of the aircraft in the simulator, but there was a tendency for the simulated aircraft to over rotate and the rate had to be arrested using the stick. The pilot also comments on a false motion cue during the intial dash that disrupts the smooth application of the cyclic and collective to begin the dash. The initial pitch down was surprising based on comments by Pilot 2 concerning the simulator FOV limiting the angle to less than 20 deg. The N-CAB chin window provided a view of the runway checkerboards and may have increased confidence to use the scene to initiate pitch down, but the feedback on attitude from the scene may have been poor. As a consequence, the simulator dash/quick-stop done by Pilot 2 was more aggressive than the flight task.

Data for Pilot 4 are shown in figures 48(a)–(e). The flight to simulator comparison of pitch attitude versus time for the dash/quick-stop task is shown in figure 48(a). Pilot 4 starts the dash with a pitch down to approximately 14 deg, but at about 28–30 knots he steps the nose down pitch to almost 20 deg and as he reaches 54 knots, he begins pitch reversal for the quick stop. Speed drifts up to 58 knots then forward speed begins to bleed rapidly. The nose up attitude for the quick stop peaks at 36 deg (pitch reversal was 56 deg in 6 sec). At this point, the pilot pushes the cyclic controller forward (in about 8 sec) to reestablish hover trim, but has to modulate the controller to bleed forward velocity to zero. This approach results in a rapid quick stop. The activity in the roll and yaw axes is shown in figures 48(b) and 48(c). Yaw rate stays within ±2 deg except for a momentary excursion during pitch reversal and quick stop where the yaw rate goes to ±5 deg. Roll attitude is steady on trim during the dash, goes slightly left wing down (−4.5 deg attitude) at the beginning of the pitch reversal, reverses to right wing down (+4 deg attitude) with modulation during the pitch reversal. Then, as cyclic is moved forward to bring nose down back to trim, the roll reverses to −9 deg attitude (left wing down) before recovery back to trim. Pilot 4 described the right-wing-down to left-wing-down reversal sensation as a sliding toward the ground. Pitch, roll, and yaw dampen quickly once trim is established. No data are available for altitude change or for the length of the dash and quick stop due to laser unlock when the higher pitch-up occurred.

The simulator data in figure 48(a) (dashed line) is slightly different due to an altered technique in the simulator. Pilot 4 attempted to do the task as a purely visual task in the simulator, but could not get satisfactory results (see comments in appendix B) and instead reverted to using cockpit information as a feedback for attitude, altitude, and speed. The simulator data show that Pilot 4 initiates the dash with a pitch-down attitude of −14 deg and as he gains speed he adjusts pitch further down to −18 deg (similar to flight test) and begins the pitch-reversal at about 55 knots and rotates to about 30 deg nose up for the quick stop. The simulated aircraft balloons up about 20 ft above the reference altitude (figs. 48(d)–(e)) during the quick stop portion of the maneuver and the aircraft yaws to the left about 15 deg. At the end of the quick stop, when the aircraft is being re-trimmed at the start of the hover, there is the right-wing-down to left-wing-down reversal with a momentary left-wing-down roll to about −12 deg attitude, which is arrested rapidly. Immediately after, Pilot 4 adjusts pitch attitude up to bleed off forward velocity before establishing hover trim. There are small oscillations in roll and some undulation in pitch, but for the

most part the attitudes dampen out as the hover continues. The top speed is 60 knots and the distance covered is about 1000 ft. Pilot 4 had difficulty with the roll attitude reversal on all three attempts in the simulator with slightly more activity in roll adjustments than demonstrated in this comparison. Statistics for the flight to simulator comparison for Pilot 2 and Pilot 4 are shown in figure 49.

Flight to simulator comparison– The dash/quick-stop task is the most difficult of the fidelity assessment tasks to analyze in terms of flight to simulator experience. The task is a multi-axis task involving coordination of pitch, roll, yaw, and heave almost simultaneously, especially for the quick stop portion of the task.

The flight test dash/quick-stop task was done with some technique differences from pilot to pilot. The differences were mainly in the quick-stop portion of the task. After pitching nose down for the dash and reaching almost 60 knots, Pilot 2 did a quick pitch reversal then held the nose-up pitch fairly constant until the forward velocity was nearly zeroed out. Pilot 2 then pushed pitch over to trim out for the hover. Pilot 4 simply went to a higher pitch up to quickly stop forward speed and then modulated the pitch attitude to bleed off the remaining forward speed to zero. Both Pilot 2 and Pilot 4 experienced a roll reversal when they pushed pitch down at the end of the quick stop. This may be because the canted tail rotor caused some coupling between yaw and roll. Both pilots had considerable activity on the controllers for stabilizing the aircraft in hover at the end of the quick stop. In the aircraft, the pilots lost reference to the horizon when they pitched nose up for the quick stop, but relied on other references to "feel" the spatial position of the aircraft. Side view was available and some down view through the bottom of the nose was available. An important reference was the ground. The pilots refer to using ground rush as a cue to altitude change. The task in the aircraft was done primarily using visual cues; the pilot scanned the outside scene and focused on the cockpit only momentarily to check instruments.

Pilot comments suggest that the dash/quick-stop task in the simulator was limited by FOV considerations. The pitch down to initiate the dash resulted in loss of the horizon and filled the scene with the flat grey checkerboard pattern on the runway. The pitch up to begin the quick stop filled the simulator windows with blue sky and there were no side windows to reference

horizon or ground. Although the N-CAB had a lower-right-hand chin window, the information presented was limited by the lack of texture (pilots could not sense ground rush) and the inability to see 90 deg to the side. The pilots altered their technique from flight to simulator to accomplish the task. The primary alteration was to rely more on the cab instruments than on the visual scene for altitude and attitude information. This was possible because, unlike the aircraft, the radar altimeter was a point-in-space reference instrument and did not change reference when the aircraft was pitched up or down. Also, the ADI had a pitch ladder. The task, more or less, became a inside-to-outside reference rather than a outside-to-inside reference task.

In the flight test, Pilot 2 experienced a moderate roll reversal from right-wing-down to left-wing-down at the end of the quick stop. In the simulator, Pilot 2 experienced a more pronounced right-wing-down roll which he quickly corrected as he finished the quick stop and re-trimmed for hover. Pilot 4 had a similar experience from flight to simulator. He was able to hold roll attitude close to trim with only a slight roll to the right during the quick stop; when he pushed pitch over to hover, he got an almost simultaneous reversal in roll to left wing down which he tried to correct quickly back to trim but got some extra oscillation in pitch and roll. The magnitude of the roll upset changed somewhat in the simulator, but the sense of the roll reversal remained the same from flight to simulator. Although the activity on the controllers to establish hover after the quick stop appears as active for both flight test and simulator, the pilots made comments about the simulated aircraft's controllability due to a lack of adequate damping.

5.3.4 Effect of Visual/Motion Phase Difference on Performance

The comments from the pilots regarding the feeling of a lack of damping in the simulator and the tendency to over control or become PIO prone in the simulator will be addressed in this section. Since the VMS motion washout logic essentially filters the motion letting the more rapid movements of shorter duration pass, but does not pass the slower ones of longer duration, an uninvited consequence is that the lower frequencies are attenuated and phase shifted ahead in time. It is thought that phase lead and attenuation reduce fidelity. Sinacori (ref. 41), in discussions with several researchers, devised a chart (fig. 50) to show

the effect of phase distortion on the fidelity of motion for angular (rotational velocity) and translational (specific force) motion. The chart gives expected fidelity (from high to low) as a function of the phase distortion (compared to the aircraft) and attenuation of the simulator angular velocity and specific force compared to those of a helicopter at a frequency of 1 rad/sec. The chart includes relations for first and second order high-pass filters at unity gain and break frequencies shown. For example, a second order washout with break frequency of 0.33 would supposedly give high fidelity motion for gains above 0.40 for the rotational velocity. The hypothesis was checked by introducing the helicopter motions to a drive logic whose filter coefficients cause the phase distortion and attenuation shown in figure 50. This test was run with a single pilot on the NASA Flight Simulator for Advanced Aircraft (FSAA), which has since been moth-balled, and although the results showed the trends predicted, the test time did not allow precise checks of the boundaries predicted.

Bray (ref. 24) has used a similar criteria for an experiment which studied the effects of vertical motion on pilot assessments of height-control handling qualities on the VMS. In his experiment he varied the break frequency, motion gain, and added delays to the aircraft response to collective-control inputs. Bray used a criteria based on his experience with the VMS and simply states in his report while speaking about the vertical axis, "If it is somewhat arbitrarily assumed that motion phase distortion up to 20 deg (lead or lag) is representative of "high fidelity" motion, it is seen that for $\omega_z = 0.2$ rad/sec, a frequency range from 0.7 to 5.0 rad/sec is so described." He concluded that the visual/motion discrepancies were not intellectually considered by the pilots and they instead attributed their difficulty in a task to poor collective response and to "reduced vertical damping."

If the criteria established by Bray for the determination of high-fidelity motion is accepted, and the assumption is made that phase distortions exceeding 20 deg will be interpreted by pilots as undesirable (possibly leading to a feeling of a lack of adequate damping), a possible explanation for the pilot comments in this experiment may be obtained. Although Bray used a parametric study to establish his criteria, and Sinacori was addressing simulator motion response versus aircraft response, the general methodology will be applied here. The reason for doing so lies with the earlier comparisons made between the aircraft and

mathematical model responses in figures 26–29 where a generally good agreement between the math model and aircraft was shown. That agreement will be used to assume that the math model represents the aircraft well enough (the pitch axis is an exception, therefore the differences between aircraft and simulator motion response shown here for the pitch axis are conservative) so that figures 32–35 (math model command to simulator motion response) can be used to determine if the test pilots exceeded 20 deg of phase distortion between math model command and motion system response when performing tasks in the simulator.

The model/motion pairs plotted in figures 32–35 are:

PB/δ_{lat} and $PSFU/\delta_{lat}$, for lateral cyclic input. QB/δ_{long} and $QSFU/\delta_{long}$, for longitudinal cyclic input. $ALTD/\delta_{coll}$ and $VZFU/\delta_{coll}$, for collective input. RB/δ_{ped} and $RSFU/\delta_{ped}$, for pedal input. The variables were defined when the comparisons were made earlier.

The first step will be to determine over what range the model command and motion response are within the 20 deg phase distortion criteria. This is done by checking figures 32–35 to establish those regions.

Figure 32 is the frequency response plot for PB/δ_{lat} and $PSFU/\delta_{lat}$. As was stated before, the plot shows that the phase curves intersect at about 2.5 rad/sec. Using the criteria of ± 20 deg from the intersection to determine the phase distortion limit, the range is established for acceptable high-fidelity motion. The range for roll rate is from 1.8 rad/sec to 4.0 rad/sec.

Figure 33 is the data for QB/δ_{long} and $QSFU/\delta_{long}$. The phase data intersect at 2.2 rad/sec and the range for 20 deg or less phase distortion is from 1.6 rad/sec to 3.0 rad/sec.

Figure 34 shows data for the vertical axis. The Bode plot shows data for $ALTD/\delta_{coll}$ and $VZFU/\delta_{coll}$. The phase curves intersect at 1.0 rad/sec and the range for high fidelity is from 0.8 rad/sec to 1.6 rad/sec.

Data for the yaw axis (RB/δ_{ped} and $RSFU/\delta_{ped}$) are shown in figure 35. The phase curves intersect at 2.5 rad/sec and the range for acceptable phase distortion is from 0.6 rad/sec to 4.0 rad/sec.

The values determined above are the boundaries for "high fidelity" motion on the simulator for the angular rates and for altitude rate. To determine if a pilot exceeded a boundary in the simulator while performing a task, the dominant frequencies (essentially the rate of change of the rate variables) in the model command and motion follow-up signals were determined and the

25

phase relationship at those frequencies was checked from the Bode plots. Time history data were used to extract the frequency content. Initially power spectral density (PSD) plots were made of the series of three tasks to see the spectral content of the data. Figure 51 shows power spectra for the roll axis variables from a time history generated by Pilot 4 while performing the side-step task. Figure 51(a) shows the input power spectra for the roll rate body axis (PB) as input and figure 51(b) is the output power spectra for the roll rate follow-up simulator motion system (PSFU). There are two distinct peaks in the input spectra (fig. 51(a)). The first peak occurs at about 1.5 rad/sec and is the dominant peak; the second peak occurs at about 4.0 rad/sec. The 1.5 rad/sec peak is outside the range of acceptable phase distortion determined from figure 32, and the 4.0 rad/sec peak is right at the edge of the acceptable region. Figure 52 illustrates the same calculation when the roll axis is not the primary axis. The figure shows input and output power spectra for PB and PSFU for the bob-up task performed by Pilot 2. The input power spectra for PB and the output spectra for PSFU (plots a and b, respectively) shows two distinct peaks at 2.8 rad/sec and at 5.5 rad/sec and simular peaks appear in the output power spectra for PSFU. In this case, the 2.8 rad/sec peak falls in the acceptable region, but the 5.5 rad/sec peak is definitely outside acceptable range. An investigation of the time history data showed that there are periods where the pilot becomes more active in pitch, roll, heave, or yaw to control the aircraft position in the task. These short periods (greater than 5 sec) of activity can be observed in the PB and PSFU traces as a rate of change of the signal with time. The frequency of this change can be calculated by determining how many cycles occur in a given time period and dividing by the time and getting the resulting frequency in rad/sec. This method was used to calculate the highest frequency for PB and PSFU trom time history traces and the frequencies calculated were very close to the high-frequency peak values shown in the PSD. This method is used as a simple means for determining the frequency of model commanded rate to the motion system rather than continuing with PSD calculations.

A comparison of the data is given in figure 53. The figure is a matrix of data for the pilots who participated in the simulation. The data presented in the figure represent input frequency (for PB, pitch rate body axis (QB), yaw rate body axis (RB), and altitude dot (ALTD)) to the motion system for each axis of interest

and for each task done. The information is taken primarily from the time history data by calculating the frequency from observed oscillations (appendix C). The three values in each box are the highest input frequencies for the three attempts made by each pilot for each task. These values represent periods of time (greater than 5 sec) where the pilot maintained an input to the motion system at that frequency. In addition to the three numbers in each box, some of the boxes have a value in an oval. These are the pilot cutoff frequencies calculated in section 5.4. The last column in figure 53 restates the high fidelity motion region (±20 deg from zero phase difference) for each axis and the frequency where the motion and model data intersect (underlined number). The data show that for some of the tasks, the pilots were operating in regions where, by the criteria selected, the fidelity of motion is less than ideal and has unacceptable phase distortion.

Bob-up— Pilot 2 gave comments about the heave axis tendency to PIO, "There seems to be a slight tendency toward PIO in heave and it's on the arrestment both going up and coming down." Note that Pilot 2 is in fact outside the region of acceptable phase distortion for all three runs for the bob-up task. In fact, he crosses boundaries in pitch, roll, and yaw. He comments on yaw, ". . . I did get yaw oscillations due to the high power pull and rotor droop, so yaw compensation was required." Pilot 4 operated outside the acceptable region (for short periods of time) in the roll, pitch, and heave axes during the bob-up task. In his original comments on completion of the task, he states, "The major compensation was the large high-frequency input to pitch and roll to maintain position." He also notes in the post run summary, "Slight tendency to PIO in collective . . . . The cyclic seems to be more lightly damped in simulator—feels loose." Pilot 5 comments on pitch axis PIO tendency, ". . . a little bit of PIO in long stick—a couple of adjustments and an overshoot of the correct pitch attitude." Pilot 5 operated outside acceptable phase boundary during the task.

Side step— Pilot 2 comments about roll axis PIO tendency, "There seems to be a tendency to PIO in the roll axis . . . [there is] a sense of low roll damping." Pilot 2 operated for periods of time outside the 20-deg phase margin. Pilot 4 comments about the stick, "The stick seems to be lighter [sec] damped or more oscillations than the aircraft." Again, Pilot 4 operated outside the region of acceptable phase for periods greater than

5 sec. Pilot 5 talks about a tendency to PIO in collective, although he operates outside acceptable limits on collective. He also has periods outside the boundaries for pitch, roll, and yaw.

Dash/quick stop— Pilot 2 operated outside the boundary on pitch, but roll, yaw, and heave remained within boundaries most of the time. He did not comment on PIO tendency. Pilot 4 operated outside the boundary in the roll axis and within boundaries on the other axes. He did not comment on PIO tendency. Pilot 5 was outside the boundary in the roll axis and slightly outside in the pitch axis. He comments he had a slight PIO tendency on pitch down to begin the dash and some tendency toward PIO in the hover after the quick stop.

Summary— Excursions out of the acceptable phase distortion region occurred for all tasks and in all axes. Often, more than one axis was out of bounds. Pilot comments seem to confirm these excursions as a feeling of a lack of damping and sometimes as a tendency for PIO.

5.4 Pilot Work Load Analysis and Cut Off Frequencies

The Cooper–Harper HQR chart used to compare HQR from flight to simulator includes subjective evaluation of pilot work load to quantify the eventual rating for a task. A quantitative assessment of pilot work load is difficult because of the contributing factors that constitute work load. Several descriptions of what constitutes work load exist. For example, Chiles (ref. 42) describes work load as, "A hypothetical concept that is determined by or (if you prefer) related to the aggregate of the task demands placed on the pilot by the system during some relatively short-duration mission or phase of a mission coupled with the action required of the pilot to satisfy those task demands." These actions by the pilot may be overt or covert, physical, oral, mental, perceptual, or any combination. Papa and Stoliker (ref. 43) describe work load as falling into three broad conceptual groupings, ". . . those related to the demands of the flight tasks—input load, those associated with the response to those demands—operator effort, and interpretations of workload based on work results or performance." Although many of the questions in the decision tree of the Cooper–Harper

scale relate to work load, the Cooper–Harper scale assessment in this construct is labeled in reference 43 as most sensitive to motor or psychomotor tasks and presumably leaves mental effort or cognitive abilities out. Modification of the Cooper–Harper scale has been done to include cognitive aspects by several experimenters (ref. 44). Mental work load is described in reference 45 as "costs" a human operator incurs in performing one task in terms of a reduction in the capacity to perform additional tasks, given that the two tasks overlap in their resource demands." For example, in combat a pilot flying a mission through unfamiliar surroundings must navigate, communicate, and control the aircraft simultaneously. Generally, assessment of mental work load is done either analytically or empirically. The analytical approaches are without the operator in the loop instead using mathematical models, expert opinion methods, or simulation models (ref. 46). Empirical work load measurements are done with the pilot in the loop and generally include performance measures, secondary task measures, subjective techniques, and physiological measures of the operator's state. Reference 45 discusses details of these approaches and applies them in a work load assessment methodology. Several studies (for example, refs. 43, 47, 48) have produced work load metrics to allow a relative scale of work load demands for tasks to be constructed for comparison and to help distinguish between control configurations. The experiment that is the subject of this report did not attempt to measure mental work load. Instead, since the Cooper–Harper scale is accepted in the handling qualities community as a work load/performance metric and was used exclusively in the present experiment; a simple comparison of pilot stick input along with the Cooper–Harper scale was used as an attempt to get a relative assessment of work load from aircraft to simulator for each subject pilot, but without comparing one pilot to another. This approach stays with the assumption that the Cooper–Harper scale is primarily sensitive to motor or psychomotor tasks.

Although the measurement of stick input gives an indication of the pilots' level of physical effort, this type of measurement has the disadvantage of being both task dependent and situation dependent and generally cannot be transferred across tasks or scenarios. The application of this approach, therefore, is limited to comparing a pilot's performance in the same task in flight and in the simulator. The assumption

27

is made (loosely) that the performance criteria and visual reference information are closely matched between flight and simulator to consider the mental workload as nearly equivalent (this neglects the cognitive process to sort out any differences), and, although the factors that contribute to differences in stick activity are not sorted by this method, a confirmation of the perceived work load (from the Cooper–Harper scale rating and comments) between flight and simulator by this simple approach may help to quickly establish comparability in future simulation fidelity assessments.

Controller input power versus frequency (the PSD) and the determination of pilot cutoff frequency from the PSD are the basic ingredients for the establishment of this relative work load. The cutoff frequency is defined here as the frequency of the half power point bandwidth of the PSD function. In the classical sense, it is the frequency at which the magnitude of the closed loop frequency response is 3 dB below its zero-frequency value (near where the input auto PSD plot begins to roll off). This calculation along with the PSD to get relative workload for a task between flight and simulator was used under the assumption that the pilot will reflect his workload in terms of the power generated for the task and that the pilot's cut-off frequency will change with work load. That is, the harder the pilot works to establish and maintain a position, the higher the input power and generally the higher the cutoff frequency. This approach does not inherently give definitive information on pilot response characteristics, as does pilot crossover frequency which would be desirable and is a truer means to measure pilot response differences between flight and simulator. The nature of the tasks make the determination of pilot crossover frequency difficult since these tasks involve large inputs (open loop) to initiate tasks and recover, and then a stabilization period in hover at the end of the task (closed loop regulation), whereas pilot crossover frequency is more easily determined by a controlled tracking task or similarly bounded task. References 49, 50, 51, and 52 give background information and methodology for measuring pilot response characteristics including crossover frequency. Although not completely definitive, the simple nature of the PSD in combination with cutoff frequency will enable a relative evaluation of pilot workload from flight to simulator.

The approach used for determining the cutoff frequency is predicated on the ability to generate a ratio of root mean square (RMS) values expressed as $\Psi_{cutoff}/\Psi_{total}$, where Ψ_{cutoff} is the RMS value at

the cutoff frequency. In this analysis, Ψ^2 is identical to the mean square value (the average of the squared values of the time history data) and RMS = $\sqrt{\Psi^2}$. The procedure to determine the ratio of RMS values is based on certain relationships from random data analysis (ref. 53). The most important relationship is between the mean square value and the PSD function expressed as

$$\Psi^2 = \frac{1}{2\pi} \int_0^\infty G_{\delta\delta} d\omega$$

where $G_{\delta\delta}$ is the auto-PSD function for the controller. In effect, the mean square value is equal to the total area under the plot of the PSD function versus frequency.

The next step is to calculate the ratio of the Ψ by forming the ratio of integrals (i.e., $\int_0^\infty$ and $\int_0^{\omega_c}$ where ω_c is the cutoff frequency) and taking the square root to get the ratio of RMS values at the cutoff frequency. This last step was done in a more direct way by using the CIFER analysis programs (ref. 28) which enabled the plotting of PSD functions and the calculation of RMS values. The ratio of RMS values to determine the cutoff frequency is known from the fact that the 3 dB down point (half power point) means that $\Psi_{cutoff}^2/\Psi_{total}^2 = 0.5$, and, therefore, $\Psi_{cutoff}/\Psi_{total} = 0.707$. The actual value of the cutoff frequency was determined by using the RMS utility program in CIFER which was set up to backout the frequency corresponding to 0.707 of Ψ_{total}.

The input auto-PSD functions were derived for a specific task from the series of three runs for each task performed by the test pilots. Data are compared for both the flight test and the simulation. The comparisons are made for the primary controller used for the task. It is recognized that the total work load is the combined activity for all axes, but the pilot activity on the primary controller should have the highest concentration of input power. The data for the bob-up task is presented first. The comparison was done primarily for FPS = off, but will occasionally refer to data with FPS = on, when necessary.

5.4.1 Bob-Up Task—Primary Controller = Collective

FPS = off– Figure 54 shows the input auto spectra generated by the four pilots who participated in the flight test. In general, the input power spectra for the flight test show similar power levels and have cutoff

frequencies in the range of 1.03–1.17 rad/s. Figure 55 shows similar data for the pilots who flew the simulator. The cutoff frequencies for the simulator pilots have more variation and range from 0.88 to 1.43. There is a difference in the power level between pilots. The averaged HQR values assigned by the pilots for the aircraft in the flight test were: Pilot 1, HQR = 2.33; Pilot 2, HQR = 3; Pilot 3, HQR = 2; and Pilot 4, HQR = 2. The average HQR values assigned to the task in the simulator were: Pilot 2, HQR= 4; Pilot 4, HQR = 4; and Pilot 5, HQR = 4.5.

An interesting comparison to make here is that two pilots (1 and 3) who participated in the flight tests had high experience in the aircraft while the other two (2 and 4) were relatively inexperienced in the aircraft (less than 50 hours). Figure 56 shows a comparison of input auto-spectra from flight test for the two experienced aircraft pilots. The figure shows similar characteristics and almost identical calculated cutoff frequency (1.05 and 1.04). When the two inexperienced aircraft pilots' input auto-spectra are compared in figure 57, their cutoff frequencies are slightly higher (1.15 and 1.20) than the experienced pilots and the spectra each have different characteristics. The calculated cutoff frequency and the RMS_{total} values for all tasks are shown in figure 58. If we compare the value of Ψ_{total} for the pilots in the table, there is an increase in Ψ_{total} from the most experienced to least experienced pilot for the task. These data do not correlate with the assigned HQR values since the pilot with the highest Ψ_{total} and highest cutoff frequency rated the task the same as the pilot with the lowest values. Since HQRs are based on perceived work load, the analysis pursues a correlation in HQR, input power, and cutoff frequency by comparing the flight test values to the simulator values for the same pilot.

Figure 59 shows the data comparison for Pilot 2. The power spectra is similar to the flight data except that the simulator data shows three peaks in the region of highest power level versus only two peaks for the flight test data. In addition, there is a more power in the frequency range 1–3 rad/sec in the simulator data. Pilot 2 shows an increase in his cutoff frequency from 1.15 in the aircraft to 1.29 in the simulator and he assigns the simulator bob-up an HQR = 4 versus an HQR = 3 for the aircraft. He comments that there is a slight bobble on arrestment of the bob-up/bob-down and that the heave damping seems low in the simulator compared to the aircraft. The peak in the simulator power spectra at about 2.5 rad/sec may reflect the bobble he

mentions. The value of Ψ_{total} increases slightly from flight to simulator (0.47 to 0.54) reflecting additional input power for the task. Figure 60 is a comparison of flight to simulator data for Pilot 4. Pilot 4 has about the same power level in the simulator as he did in flight (Ψ_{total} = 0.565 for flight, and Ψ_{total} = 0.58 for simulator), but there are more bumps on the simulator spectra curve indicating more activity at multiple frequencies. There is also an increase in the pilot cutoff frequency from 1.20 in flight to 1.43 in the simulator and the pilot assigns a value of HQR = 4. He comments that the work load has increased in the simulator and that he has to work the cyclic (which effects collective) more to maintain position than he had to in the aircraft. Figure 61 shows data for Pilot 5 in the simulator. Pilot 5 did not participate in the flight test and his data will only be compared to the other simulator pilots. Pilot 5 has a much lower cutoff frequency and lower power level than the other two pilots and assigns the task in the simulator (FPS = off) a value of HQR = 4.5, but comments that the cyclic stick force feels much reduced in the simulator compared to the aircraft and as he applies cyclic he gets into pitch overshoot problems and an increased work load. These problems were investigated in section 5.3.4.

The simulator data also gives an opportunity to test the hypothesis of reduced cutoff frequency and power correlation with reduced work load. Figures 61, 62, and 63 include data for the bob-up task with FPS = on in the simulator. The FPS = on provides full-time heading hold and attitude hold. These features should off-load the pilot somewhat and should reduce pilot work load in the task. The assigned HQR values are: Pilot 2, HQR = 3; Pilot 4, HQR = 3; and Pilot 5, HQR = 4. Pilot 2 (fig. 62) rated the FPS = on better than the FPS = off case, but actually increased his cutoff frequency slightly and his Ψ_{total} remained the same (fig. 58). The characteristic of the power spectra for Pilot 2 changed slightly with fewer peaks for the FPS = on case. Pilot 2 commented that heading hold was the work reducer; he did not have to correct as much for collective-to-yaw coupling, which may account for the slightly different spectra. Pilot 4 (fig. 63) reduced his cutoff frequency for the task and had a corresponding lower HQR value, although his Ψ_{total} values remained about the same. The auto-PSD for Pilot 4 is smoother and less peaked for the FPS = on case than for the FPS = off case, which may indicate a more controlled input to the controller. Pilot 5 (fig. 61) had about the same cutoff frequency and Ψ_{total} and

his spectra almost coincide. He gave gave about the same HQR value. Although the data are somewhat inconclusive, note that the PSD plots for Pilots 2 and 4 seem to reflect a difference in activity, with the spectra becoming smoother for the FPS = on case.

Summary– The comparison of data from flight to simulator for the bob-up task showed that the input power and cutoff frequency increased from flight to simulator for the pilots who flew in both. Comparing power levels attained during a task from pilot to pilot does not correlate with their respective HQR values, but comparing power level for the same pilot from flight test to simulator indicates that an increase in power and cutoff frequency generally resulted in a worse HQR value. The input PSD functions also reflected a change of activity on a controller. The flight data had fewer peaks than did the simulator data for the same task. The extra peaks in the simulator data indicate concentrated inputs at those frequencies versus less activity for the flight case. There was more activity on the controllers in the simulator.

5.4.2 Side Step—Primary Controller = Lateral Cyclic

The side-step maneuver was a short side step of 40 ft between the horizontal hover boards. The level of aggression was limited by the spacing and the ability to stabilize the aircraft after the lateral quick stop to stop on the opposite board. Figure 64 shows a comparison of the side-step maneuver from the flight test aircraft with the FPS off. The data for the four pilots show that for the flight test maneuver the four pilots had cutoff frequencies from 1.17 to 1.33 and all have about the same level of input power (fig. 58). The average pilot ratings for the task are: Pilot 1, HQR = 2.3; Pilot 2, HQR = 3; Pilot 3, HQR = 3; Pilot 4, HQR = 2. When the task is repeated in the simulator, as shown in figure 65, the pilot cutoff frequencies range from 1.26 to 1.81 and the power level is radically different from pilot to pilot. The average pilot ratings for the task in the simulator are: Pilot 2, HQR = 4; Pilot 4, HQR = 4; Pilot 5, HQR = 3. A direct comparison from flight to simulator can be made for Pilot 2 and Pilot 4. Both of these pilots increased their cutoff frequency from flight test to simulator. Pilot 2 (fig. 66) went from 1.29 to 1.81 and Pilot 4 (fig. 67) went from 1.24 to 1.48. Both pilots raised their HQR values for the task in the simulator—Pilot 2, from HQR = 3 to HQR = 4, and

Pilot 4 from HQR = 2 to HQR = 4. Pilot 2 comments for the simulator task that a lack of roll damping creates a tendency for PIO. His simulator data shows a higher peak power which is reflected in figure 58, but the data is reasonably smooth with a shift upward in frequency for the peak. Data for Pilot 4 shows lower power in the simulator, but shows additional peaks at about 4 rad/sec. Pilot 4 comments that he was more aggressive in the aircraft, "I think I was more aggressive in the aircraft because you can just put in a bank angle, charge it over, and come to a screeching stop." In the simulator he comments, "Here I put in that bank angle [aircraft bank angle], get it started; I am going to take it off right away [take out bank angle] or I am going to find myself at a large bank angle at the other end and then fight it to stop. It is the lateral oscillation that comes when stabilizing the large input that eats up the time." He further comments, "I don't like the stick characteristics, particularly around center position. The stick seems [to be more] lightly damped or more oscillatory than the aircraft." This pilot also comments on the need for active pedal to maintain heading with FPS = off, and found the simulated aircraft harder to hover. The peak at about 3 rad/sec may reflect the light stick and additional activity. The simulator input auto-power spectra bump or increase in magnitude at about 4 rad for the FPS = off case may fall in a region where there is phase mismatch between model and motion. Pilot 5 has the lowest power level in the simulator. The spectra is smooth with slight peaks showing up at about 3 and 5 rad/sec. Pilot 5 comments that the roll rates were predictable, but he felt a little tendency toward PIO in collective.

A comparison with the FPS = on can be made with the simulator data. Figure 68 shows auto-PSD data for the three pilots in the simulation. The curves are still spread out from pilot to pilot, but the cutoff frequencies are reduced for Pilot 2 and Pilot 4. Pilot 5 stayed at about the same cutoff frequency for FPS = on as he had for the FPS = off case. The average HQR values assigned are: Pilot 2, HQR = 4; Pilot 4, HQR = 2; Pilot 5, HQR = 3. An interesting note here is that Pilot 2 reduced cutoff frequency from 1.81 to 1.68, although he did not change his rating, but the spectra show more oscillation in the region 3–5 rad/sec than he had for the FPS = off case, thus indicating some increased activity in those regions. Pilot 2 comments that the FPS as implemented in the simulator is jerky and not as smooth as in the aircraft. Since the FPS causes the stick to migrate,

more force is required to overcome the feedback and Pilot 2 found the simulator implementation objectionable. Pilot 4 changed cutoff frequency from 1.48 to 1.36 and changed his rating from HQR = 4 to HQR = 2. His spectra are smooth except for the small bump up at about 5 rad/sec and he shows less power over the region 1–2.5 rad/sec than for the FPS = off case. Pilot 4 commented that he backed off in aggressive approach and made smaller inputs to avoid oscillations and to smooth the maneuver to stay within time constraints on the task. Pilot 5 did not change cutoff frequency and gave the same rating as with FPS = off.

Summary– FPS = off: The side-step data PSD function had a definite increase in power level and an increase in cutoff frequency from flight to simulator for Pilot 2 and his HQR in the simulator is worse. Pilot 4 actually decreased the power from flight to simulator but had an increased cutoff frequency, and the simulator power spectra showed more peaks than the flight data. His rating in the simulator was worse by two points over the flight case. **FPS = on:** Pilot 2 had problems with the FPS implementation in the simulator and rated the FPS = on the same as he rated the FPS = off in the simulator. Although his cutoff frequency was reduced for the FPS = on case, there are more oscillations in the power spectra than for the FPS = off case. Pilot 5 had about the same experience for FPS = on and FPS = off and gave each case the same rating.

5.4.3 Dash/Quick Stop—Primary Controller = Pitch Cyclic

The dash/quick-stop maneuver is different in nature compared to the bob-up and the side-step maneuvers. The dash/quick-stop was performed in a free form manner without the constraints of the hover board. The maneuver was basically a dash to 60 knots followed immediately by a quick stop to a hover. The quick stop was done about the tail wheel. The pilot was given performance criteria (see section 4.1.4) for desired performance which included altitude constraint during the dash, a balloon altitude limit during the quick stop, and final altitude and heading limits for the stabilized hover required at the end of the maneuver. The total distance for the dash and the quick stop covered about 1000 ft. Although the whole maneuver was not as constrained as the hover board tasks, the procedure of using the input auto spectra to compare

the pilot's input power in flight to that used in the simulator will be applied as a relative measure of the workload expended during the task. The dash/quick-stop maneuver eventually involves all axes in the stabilization to the hover position at the end of the task, but the primary control actions take place with the pitch cyclic when initiating the dash and when arresting the quick stop. Comparisons will be made, as before, between flight test and simulator, but if the pilot comments indicate other axis problems during the task, additional axes may be investigated. The analysis is for data with the FPS = off.

Figure 69 shows the input power spectra data for all four pilots who performed the dash/quick-stop task in the flight test. The data for the pitch cyclic shows that the pilots had about the same power level and their cutoff frequencies were close together. The range in cutoff frequency was from 0.44 to 0.50 rad/sec; Pilot 1 had the highest cutoff frequency and Pilots 2, 3, and 4 had about the same values (0.44, 0.45, and 0.46, respectively). The input power levels at these cutoff frequencies changed about 4 dB from lowest to highest value. The interesting thing about this data is that when the dash/quick-stop data was collected from the flight tests, Pilots 1 and 2 flew together and had about the same power levels and on another day, Pilots 3 and 4 flew together and had about the same power levels. The difference of 4 dB shown in figure 69 therefore appears to be the difference in the day of test rather than a difference between pilots. The similarity for data from these two sets of pilots indicates that the dash/quick-stop task was performed in a similar manner by all pilots.

The comparisons for the simulator pilots are shown in figure 70. The power levels for the three test pilots are similar to the flight test case, but the spread in maximum power levels is only about 2 dB. The cutoff frequencies are slightly higher than the flight test data (from 0.47 to 0.54), but not significantly. These results are reflected in the HQRs given by the pilots who participated in both the flight test and the simulation. The HQR values are the same for Pilot 2 and only one rating point higher in the simulator for Pilot 4. Results for these pilots are given below.

Pilot 2—Flight HQR = 4, Simulator HQR = 4– Figure 71 shows data for Pilot 2 comparing the input auto spectra for flight test and the simulator for pitch cyclic input. The data show that Pilot 2 had about the

31

same power level for the flight test and the simulator with a slightly higher power level in the simulator from the peak to about 2 rad/sec and then the simulator power level falls slightly below the flight test data for the rest of the spectra. The flight data (solid line) has more high frequency power (above 3 rad/sec) with several peaks as frequency increases. The pilot comments that he is working harder in the pitch axis for the simulation task, but the higher work load is a result of constant monitoring from scene to cockpit to check attitude and altitude.

Pilot 4—Flight HQR = 3, Simulator HQR = 4— Figure 72 shows data for Pilot 4 comparing flight test to simulator. The data for pitch cyclic input show that the peak power level has been reduced slightly in the simulator, but becomes coincident with the flight test data from about 1 rad/sec and above. Pilot 4 has rated the simulator task at HQR = 4 indicating that his work load was higher in the simulator and crosses the boundary to a Level 2 rating. Comments from the questionnaire indicate that the pilot had problems in the simulator with the lack of texture and a side view, so he changed the task from outside to inside the cockpit because of the lack of cues. He further comments that he had some problems with over-controlling pitch and collective to avoid excessive ballooning in the quick stop since the simulated aircraft had a natural tendency to pitch up. The changes in collective and cyclic were small, but were frequent enough to have to work harder to get everything in the right direction.

Lateral cyclic input— The data for the simulation for Pilot 4 is quite different in nature. Pilot 4 has three distinct peaks in the auto spectra in the simulation (fig. 73). The rounded peaks occur at approximately 2, 5, and 9 rad/sec. These oscillations may have contributed to the additional work felt on the cyclic.

Pilot 5—Simulator HQR = 6— The power spectra for Pilot 5 is at about the same level as the other pilots and the cutoff frequency is comparable (figs. 70 and 58). His higher HQR value (high Level 2) is much worse than the other two pilots in the simulator. Pilot 5 tried to use the visual scene for cuing, but had difficulty with spatial positioning. He also experienced the same false motion cue on acceleration that Pilot 2 did. The reliance on the visual scene and loss of FOV at times resulted in many overshoots and corrections (his power spectra show more power in the frequency range above 2 rad/sec and several bumps versus the other pilots' fewer bumps). The additional work load due to overshoots caused a higher HQR value.

Summary— The dash/quick-stop task had about the same power levels in the simulator with only a slight increase in cutoff frequency for the two pilots who flew in the flight test and in the simulator. The assigned HQR values were the same for Pilot 2 and only one rating point worse in the simulator for Pilot 4. Pilot 4 comments that he was forced to change his approach in the simulator versus the flight because of a lack of cues. Both pilots used cockpit instrumentation in the simulator to fly the task with less reliance on the visual and, as a result, reported increased work load from constant checks between the visual and the instruments. Pilot 5 tried the task as a purely visual task without much success due to lack of reasonable visual cues and his rating was much worse than those given by Pilots 2 and 4.

5.5 Summary of Results

The results are summarized below for the fidelity assessment of the UH-60A Gen Hel Black Hawk simulation:

1. The real-time UH-60A Gen Hel mathematical model used for this experiment shows good agreement with the aircraft. Time history data of step inputs to the controllers and the resulting aircraft/simulation responses were taken for hover, 60 knots, and 100 knots and are shown in references 13 and 19 and in figure 23 (hover only). Piloted frequency sweeps of the controllers in the aircraft and in the simulator (done for this experiment) show that the model compares favorably with the aircraft in roll, heave, and yaw axes dynamics (figs. 26, 28, and 29). The pitch axis comparison (fig. 27) was compromised by poor coherence in the flight data reducing confidence in pitch axis results. Overall, the time and frequency domain data show that the UH-60A Gen Hel mathematical model is a good representation of the UH-60A helicopter.

2. The HQRs from the 1989 back-to-back flight test and simulation compare well. The 1990 simulation tends to have worse HQRs. The flight test data are generally in Level 1. The bob-up and side-step ratings from the flight test are in the HQR range 2–3 and the dash/quick-stop ratings are in the HQR 3–4 range. The simulator data overlaps the flight test data, but is generally tending toward Level 2. The July 1989 data

shows the best agreement with the flight, with bob-up HQR ranging from 2.5–3.5 on average and side-step data ranging from 3–4. The dash/quick-stop values range from HQR 3–4, the same as the flight test. The January 1990 HQRs tend to have more scatter and are more into the Level 2 range. The bob-up data ranges from HQR 3.5 to 4.5; the side-step HQR ranges from 3.0 to 4.0; and the dash/quick-stop ranges from 3.5 to 6.

3. Pilot comments on the general behavior of the aircraft versus the simulator stress the predictability of response in the tasks. The aircraft in flight test showed good damping characteristics, controllability was not a factor, and the pilots felt confident with spatial positioning. Comments from the simulation were about the inability to get a predictable response from the simulated aircraft. There was a tendency to concentrate on one axis at a time to sort out problems, and less confidence in establishing/maintaining spatial position. Pilots commented on the lack of damping and of their tendency to get into a PIO.

4. Pilot comments for both the 1989 and 1990 simulations were critical of the image presentation in terms of FOV, the lack of detail/texture, image blurring, and the lack of depth perception. These factors resulted in an inability to feel spatial position and to sort out individual axis changes. The pilots were unable to distinguish small changes in roll versus yaw and had equal difficulty with small changes in pitch versus altitude. These factors resulted in the following:

• The hover board targets in the simulation were a geometric duplicate (no texture in simulation) of the targets used in the flight test. However, in the bob-up task, the inability to see the upper hover target on bob-up or the lower target on bob-down resulted in abrupt controller inputs and overshoot of the targets. This was followed by bobbles in stabilizing the hover. In addition, the lack of a ground closure cue on bob-down made the task more unpredictable. The side step presented similar problems and pilots experienced overshooting and bobbling when trying to stabilize hover at the end of the task.

• The dash/quick-stop task was compromised by the restricted FOV, image blurring when pitching down to initiate the dash, and lack of detail/texture for ground closure cues during the quick stop. These shortcomings led to an alteration of technique from flight to simulator from a mostly out-the-window task to a mostly cockpit-instrument-monitoring task.

5. Comparison of time history data from the flight test with the 1990 simulation show that the simulator inputs are much crisper and are generally larger in magnitude indicating that the pilots were more aggressive in the simulator. The time history data from the simulator shows the overshoot and bobbles and the extra activity in all axes to stabilize on the hover board targets during the bob-up and the side-step tasks. Data for the dash/quick-stop task show larger pitch angles for the dash and for the quick stop in the simulator even though the pilots sometimes perceived that the angles were not as large in the simulator as they were in flight.

6. The relative workload analysis applied to the flight test and to the 1990 simulation data show that pilot cutoff frequency and power level for the input auto power spectra were generally higher in the simulator than in flight for the tasks. These results correlate with a higher workload experience and generally corroborate the worse HQR ratings given in the simulator.

7. Commanded input frequency (the rate of change of the signal in question) to the motion system was calculated from time histories. The data from angular rate and heave rate were checked against Bode plots of model/visual/motion (figs. 32–35 and 58) and show that the pilots were occasionally operating outside acceptable limits on phase distortion for high fidelity motion and generally were in the region where motion lags the model/visual by more than 20 deg. These excursions into higher phase distortion occurred at the top of the bob-up during hover stabilization, at the bob-down hover point, on arrestment of the side steps, and in the stabilization period for the quick stop after the dash. Sometimes more than one axis was involved. Operation in regions of higher phase distortion may account for the apparent lack of damping and the tendency for PIO.

8. Pilots complained that the cyclic stick had insufficient damping in the simulator and may have contributed to higher workload for some tasks.

9. The simulator seat shaker provided a good indication of the translational lift region at about 15 knots. Even though the amplitude was set to a low value to avoid pilot fatigue, the proprioceptive cue was considered helpful during the tasks. Aural cuing was sometimes good (bob-up and side step), but at other times the dynamic change did not reflect the expected change as was experienced in the aircraft (dash/quick stop).

6 CONCLUSIONS

Although the UH-60A Black Hawk helicopter mathematical model compares well with the aircraft, the fidelity of the overall simulation is still lacking in some areas. Conclusions from the results are as follows.

1. Improvements since 1982 have refined the UH-60A Gen Hel mathematical model to be more representative of the UH-60A helicopter dynamics. Model refinements since 1982 proved to be valuable additions. These refinements include correction and expansion of the rotor-blade equations of motion, improvements to the T700 engine and drive-train model, replacement of the flight control and stabilator control systems models, including expansion the FPS model to get back-driving of the stick and the addition of pedal microswitches for turn coordination and heading hold logic. These improvements and others are summarized in references 13 and 19.

2. The performance of a flight test back-to-back with the simulation showed overlap in the HQR values with a favorable impression of the simulator given in pilot comments. The simulation performed only six months later shows a wider spread in the HQR values and less favorable comments on the simulator experience. It appears as if the flight experience was enhanced with passing time and unfavorable flight characteristics were forgotten. Although there was overlap in HQR values from flight to simulator, some issues relating to the fidelity of the simulation are not sorted out by the pilot ratings. The remaining conclusions are possible reasons for lack of fidelity in the simulator.

3. The hover board targets in the simulator image presentation made the tasks done against the boards in the simulator almost identical to the tasks performed in the flight tests. The pilots commented that they used the same strategy in flight test and simulator. The simulator image presentation, however, was not completely adequate for the tasks. For example,

• *Field-of-view* in the simulator was not adequate for the bob-up and side-step tasks because the pilots could not see the stop points for the tasks until they were nearly on top of them. They could not see the top target during the bob-up, the bottom target during the bob-down, or the left and right target boards during side steps when the boards were in the horizontal position. This took away their ability to predict a stopping point and smoothly lead the stop. Instead, they overshot the stopping points and had to make very large corrections to re-acquire the target. This degraded the HQR. For the dash/quick-stop task, FOV was inadequate because the loss of visual cues during the pitch down at the beginning of the dash and at the pitch up to quick stop resulted in the pilots altering the task from a visual-reference task to an instrument-monitoring task centered in the cockpit.

• *Image clarity* was not adequate. The image resolution was poor and resulted in confusion on spatial position from the lack of depth perception. On occasion, pilots could not distinguish between a yaw change or a roll change, or a pitch change versus a change in altitude. The lack of detail/texture in the scene reduced the pilots' ability to sense small changes in drift, and they could not detect closure to the ground.

4. Time history data showed that pilots were more aggressive in the simulator. Pilots with limited flight experience in the aircraft were cautious in the flight test, but if they were experienced simulator pilots, they were more aggressive in the simulator than they were in flight. They made larger initial inputs in the simulator and, consequently, had to make larger corrections when they built up higher rates and got more oscillations. This may be due to the pilots' inability to pick up velocity cues and small position changes from the computer generated visual scene (they want to see a change in their scene due to a controller input) or they have disregarded the fear factor in the simulated vehicle. It may be necessary to increase the quality of vibration and aural cuing to introduce a more realistic sense of aircraft drive train response, and the image presentation must be improved to show small changes.

5. The relative work load analysis using input power spectra showed an increased power level and/or cutoff frequency for the tasks in the simulator over the values produced in flight. Generally the increased power and/or cutoff frequency correlated with a higher (worse) HQR assigned by the pilot. The power spectra shapes were also good indicators of increased activity for a task in the simulator versus the aircraft. The PSD technique worked best on the bob-up and the side-step tasks since they were constrained by the hover board targets and position regulation was visual feedback. The application of this tool to the dash/quick-stop task was not as satisfactory due to the open-ended nature of the task.

6. At times, pilots operated in regions where phase distortion exceeded 20 deg (outside the region defined for high fidelity motion) between the aircraft math model and motion and visual cues. These periods were

often experienced as a lack of damping in the simulated aircraft. The region of "high fidelity" motion must be increased without compromising necessary onset accelerations. It may be necessary to tailor each axis washout algorithm to avoid excursions into poor fidelity regions. One approach is to use online analysis tools and readouts, to set the washout for a task to avoid high phase distortion. The end result may be a lowered magnitude of response, but less contribution of the motion system to the feeling of a lack of damping in the simulated aircraft.

7. The force-feel system in this simulation lacked the "feel" of the aircraft controls in flight. The stick damping and friction were difficult to duplicate due to undetermined effects of vibration and mechanical linkage on the flight controllers in the aircraft. Although a nominal set of setup values was used for this simulation, additional adjustment parameters may need to be added to the math model to improve controller performance.

REFERENCES

1. Sinacori, J. B.: Validation of Ground Based Simulation. Presented at the 25th Annual Forum of the American Helicopter Society, Washington, D.C., May 1969.

2. Ferguson, S. W.; Hanson, G. D.; and Churchill, G. B.: Simulation Validation of the XV-15 Tilt-Rotor Research Aircraft. Presented at the 40th Annual Forum of the American Helicopter Society, Arlington, VA, May 1984.

3. Paulk, C. H., Jr.; Astill, D. L.; and Donley, Shawn F.: Simulation and Evaluation of the SH-2F Helicopter in a Shipboard Environment Using the Interchangeable Cab System. NASA TM-84387, Aug. 1983.

4. Anderson G. R.: A Method for Aircraft Simulation Verification and Validation Developed at the United States Air Force Flight Simulation Facility. AGARD Conference Proceedings No. 408, Flight Simulation, Paper No. 20, AGARD-CP-408, Sept. 30–Oct. 3, 1985.

5. White, A. D.: Hall, J. R.; and Tomlinson, B. N.: Initial Validation of an R and D Simulator with Large Amplitude Motion. AGARD Conference on Piloted Simulation Effectiveness, AGARD Conference Proceedings No. 513, AGARD-CP-513, Feb. 1992.

6. Cooper, G. E.; and Harper, R. P., Jr.: The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, Apr. 1969.

7. Howlett, J. J.: UH-60A Black Hawk Engineering Simulation Program: Vol. I—Mathematical Model. NASA CR-66309, Dec. 1981.

8. Nagata, J. T., et al.: Airworthiness and Flight Characteristics Evaluations, UH-60A (Black Hawk) Helicopter. USAAEFA 77-17, 1981.

9. Operator's Manual, UH60A and EH-60A Helicopter. TM 55-1520-237-10, Jan. 1988.

10. Clement, W. F.; Cleveland, W. B.; and Key, D. L.: Assessment of Simulation Fidelity Using Measurements of Piloting Technique in Flight. AGARD Conference Proceedings No. 359, Monterey, CA, May 1984.

11. Ferguson, S. W.; Clement, W. F.; Cleveland, W. B.; and Key, D. L.: Assessment of Simulation Fidelity Using Measurement of Piloting Technique in Flight. American Helicopter Society 40th Annual Forum, May 1984.

12. Cleveland, W. B.; and Atencio, A., Jr.: Effects of Simulator Variations on the Fidelity of a UH-60 Black Hawk Simulation. Proceedings of the Conference on Aerospace Simulation II, San Diego, CA, Jan. 1986.

13. Ballin, M. G.: Validation of a Real-Time Engineering Simulation of the UH-60A Helicopter. NASA TM-88360, Feb. 1987.

14. Ballin, M. G.: A High Fidelity Real-Time Simulation of a Small Turboshaft Engine. NASA TM-100991, July 1988.

15. Kaplita, T. T.: UH-60 Black Hawk Engineering Simulation Model Validation and Proposed Modifications. NASA CR-177360, June 1984.

16. McFarland, R. E.: Establishment of a Rotor Model Basis. NASA TP-2026, June 1982.

17. McFarland, R. E.: The N/Rev Phenomenon in Simulating a Blade Element Rotor System. NASA TM-84344, Mar. 1983.

18. Ferguson, S. W.; Jewell, W. F.; and Clement, W. F.: UH-60A Black Hawk Flight Test and Simulation Investigation Final Report. Technical Report 1242-1, Systems Technology, Inc., June 1987.

19. Ballin, M. G.; and Dalang-Secre'tan, M-A.: Validation of the Dynamic Response of a Blade-Element UH-60 Simulation Model in Hovering Flight. Presented at the 46th Annual Forum of the American Helicopter Society, Washington, D.C., May 1990.

20. Schroeder, J. A.; Moralez, E.; and Merrick, V. K.: Simulation Evaluation of the Control System Command Monitoring Concept for the NASA V/STOL Research Aircraft (VSRA). AIAA Paper 87-2255, Aug. 1987.

21. Bailey, F. J., Jr.: A Simplified Theoretical Method of Determining the Characteristics of a Lifting Rotor in Forward Flight. NACA Report 716, Mar. 1941.

22. Ellison, D.; and Mattham L.: USAF Stability and Control DATCOM. Flight Control Division, Air Force Dynamics Laboratory, Wright-Patterson Air Force Base, Sept. 1970.

23. Danek, G.: Vertical Motion Simulator Familiarization Guide. Replacement for ARC 275A (Feb. 1981), Oct. 1991.

24. Bray, R. S.: Visual and Motion Cuing in Helicopter Simulation. NASA TM-86818, Sept. 1985.

25. Mitchell, D. G.; Hoh, R. H.; Atencio, A., Jr.; and Key, D .L.: Ground-Based Simulation Evaluation of the Effects of Time Delays and Motion on Rotorcraft Handling Qualities. USAAVSCOM TR 91-A-010, Jan. 1992.

26. Blanken, C. L.; Hart, Daniel C.; and Hoh, Roger H.: Helicopter Control Response Types for Hover and Low-Speed Near-Earth Tasks in Degraded Visual Conditions. Presented at the 47th Annual Forum of the American Helicopter Society, Phoenix, AZ, May 1991.

27. Tischler, M. B.: Frequency-Response Identification of XV-15 Tilt-Rotor Aircraft Dynamics. NASA TM-89428/USAAVSCOM TM 87-A-1, May 1987.

28. Tischler, M. B.; and Cauffman, M. G.: Frequency-Response Method for Rotorcraft System Identification with Applications to the BO-105 Helicopter. Presented at the 46th Annual Forum of the American Helicopter Society, Washington, D.C., May 1990.

29. Farrell, R. J.; and Booth, John M.: Design Handbook for Imagery Interpretation Equipment. Boeing Aerospace Company, D-180-19063-1, Feb. 1984.

30. McFarland, R. E.: Transport Delay Compensation for Computer-Generated Imagery Systems. NASA TM-100084, Jan. 1988.

31. Memo from R. E. McFarland to D. L. Key. Feb. 1990.

32. McFarland, R. E.; and Bunnell, J. W.: Analyzing Time Delay in a Flight Simulation Environment. Presented at the AIAA Flight Simulation Technologies Conference and Exhibit, Dayton, OH, AIAA Paper 90-3174, Sept. 1990.

33. Baron, S.; Lancraft, R.; and Zacharias, G.: Pilot/vehicle Analysis of Visual and Motion Cue Requirements in Flight Simulation. NASA CR-3312, Oct. 1980.

34. Tailby, A. J.; and Downey, D. A.: Simulation Validation of the VMS/UH-60. AEFA Project Report 89-95, Sept. 1989.

35. Hess, R. A.; and Malsbury T.: Closed-Loop Assessment of Flight Simulator Fidelity. Journal of Guidance, Control and Dynamics, vol. 14, no. 1, 1991, pp. 191–197.

36. Hess, R. A.: Feedback Control Models. Chap 9.5, Handbook of Human Factors, G. Salvendy, ed., Wiley, 1987, pp. 663–676.

37. Hess, R. A.: A Model Based Theory for Analyzing Human Control Behavior. Advances in Man-Machine Systems Research, vol. 2, W. Rouse, ed., JAI Press, 1985, pp. 129–176.

38. Hess, R. A.; and Mnich, M. A.: Identification of Pilot-Vehicle Dynamics Using In-Flight Tracking Data. Journal of Guidance, Control and Dynamics, vol. 9, no. 4, July–Aug. 1986, pp. 433–440.

39. Hess, R. A.; and Yousefpor, M.: Analyzing the Flared Landing Task with Pitch-Rate Flight Control Systems. Journal of Guidance, Control, and Dynamics, vol. 15, no. 3, May–June 1992, pp. 768–774.

40. Hess, R. A.; Malsbury, T.; and Atencio, A., Jr.: A Model-Based Assessment of Rotorcraft Flight Simulator Fidelity in a Lateral Translation Maneuver. Journal of Guidance, Control, and Dynamics, vol. 16, no. 1, Jan.–Feb. 1993, pp. 79–85.

41. Sinacori, J. B.: The Determination of Some Requirements for a Helicopter Flight Research Simulation Facility. NASA CR-152066, Contract NAS2-9421, Sept. 1977.

42. Chiles, W. D.: Objective Methods for Developing Indices of Pilot Workload. FAA-AM-77-15, July 1977.

43. Papa, R. M.; and Stoliker, J. R.: Pilot Workload Assessment—A Flight Test Approach. AGARD-CP-425, Oct. 1987

44. Wierwille, W. W.; and Casali, J. G.: A Validated Rating Scale for Global Mental Workload Measurement Applications. Proceedings of the Human Factors Society, 27th Annual Meeting, Oct. 10–14, 1983.

45. Grenell, J. F.; Kramer, A. F.; Sirevaag, E. J.; and Wickens, C. D.: Advanced Workload Assessment Techniques for Engineering Flight Simulation. Proceedings from the 47th Annual Forum of the American Helicopter Society, Phoenix, AZ, May 6–8, 1991.

46. Lysaght, R., et al.: Operator Workload: Comprehensive Review and Evaluation of Operator Workload Methodologies. Analytics Technical Report 2075-3, Willow Grove, PA, 1989.

47. Hart, S. G.; Battiste, V.; and Lester, P. T.: A Supervisory Control Simulation for Workload and Performance Research. Proceedings of the 20th Annual Conference on Manual Control, NASA CP-2341, June 1984.

48. Reid, Gary B.; Eggemeier, F.; Thomas, ; and Nygren, T. E.: An Individual Differences Approach to SWAT Scale Development. Proceedings of the Human Factors Society, 26th Annual Meeting, Oct. 25–29, 1982.

49. McRuer, D. T.; and Krendel, E. S.: Mathematical Models of Human Pilot Behavior. AGARDograph No. 188, AGARD-AG-188, Jan. 1974.

50. McRuer, D.; Graham, D.; Krendel, E.; and Reisener, W., Jr.: Human Pilot Dynamics in Compensatory Systems—Theory, Models, and Experiments with Controlled Element and Forcing Function Variations. Technical Report No. AFFDL-TR-65-15, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, July 1965.

51. Jewell, W. F.; and Schulman, T. M.: A Pilot Control Strategy Identification Technique for use in Multiloop Control Tasks. NASA CR-152374, Aug. 1980.

52. Newell, F. D.; and Pietrzak, P. E.: In Flight Measurement of Human Response Characteristics. Journal of Aircraft, vol. 5, no. 3, May–June 1968.

53. Bendat, J. S.; and Piersol, A. G.: Random Data Analysis and Measurement Procedures. Wiley–Interscience, 1971.

Pilot – vehicle system

(a)

Pilot – simulated vehicle system

(b)
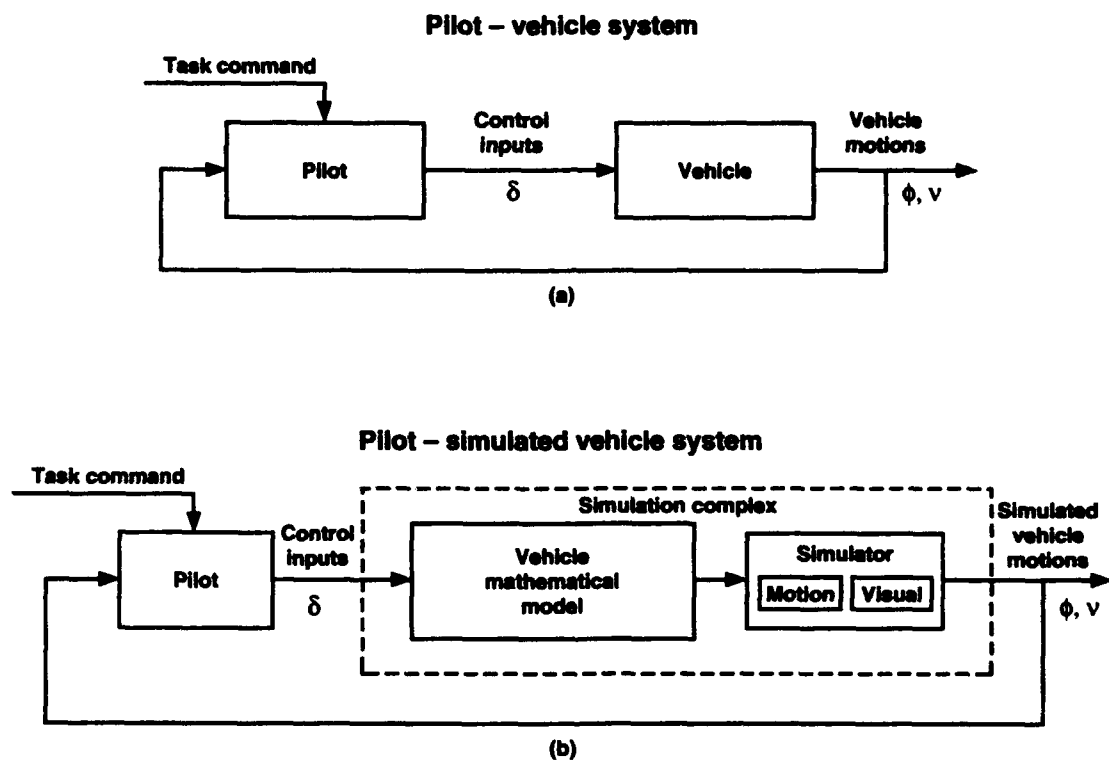
Figure 1. Flight vs. simulation operational block diagrams.
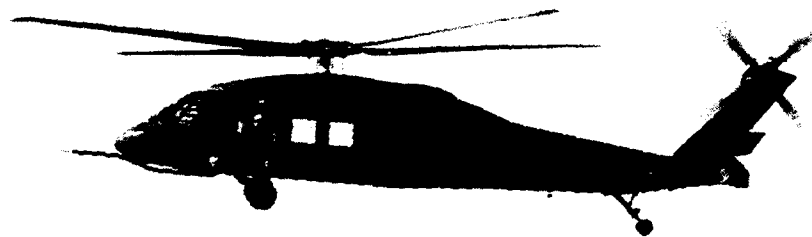
Figure 2. UH-60A Black Hawk helicopter.
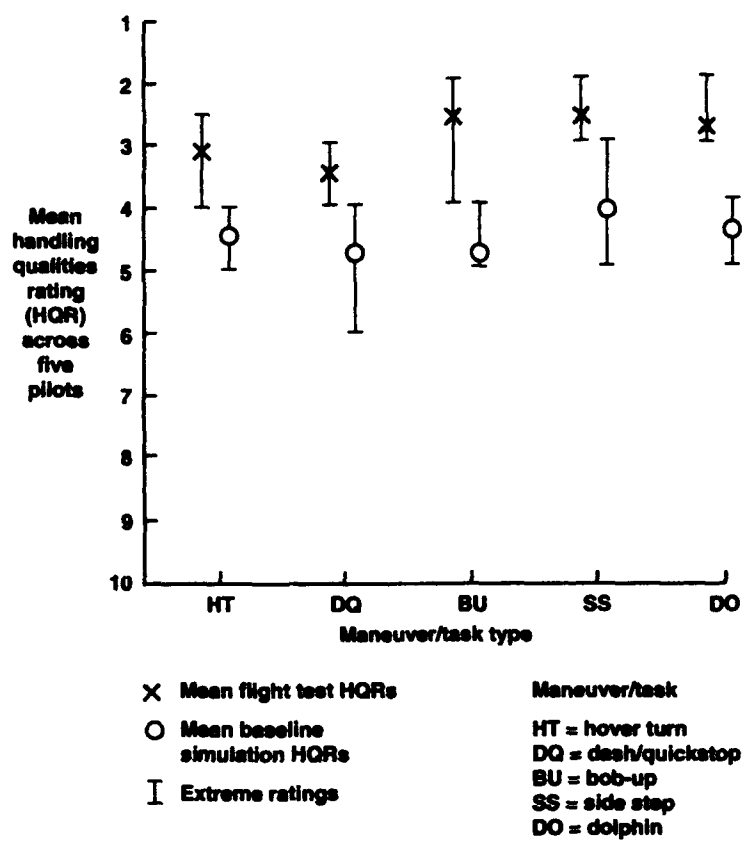
Figure 3. Handling qualities rating data for the 1982 simulation validation.
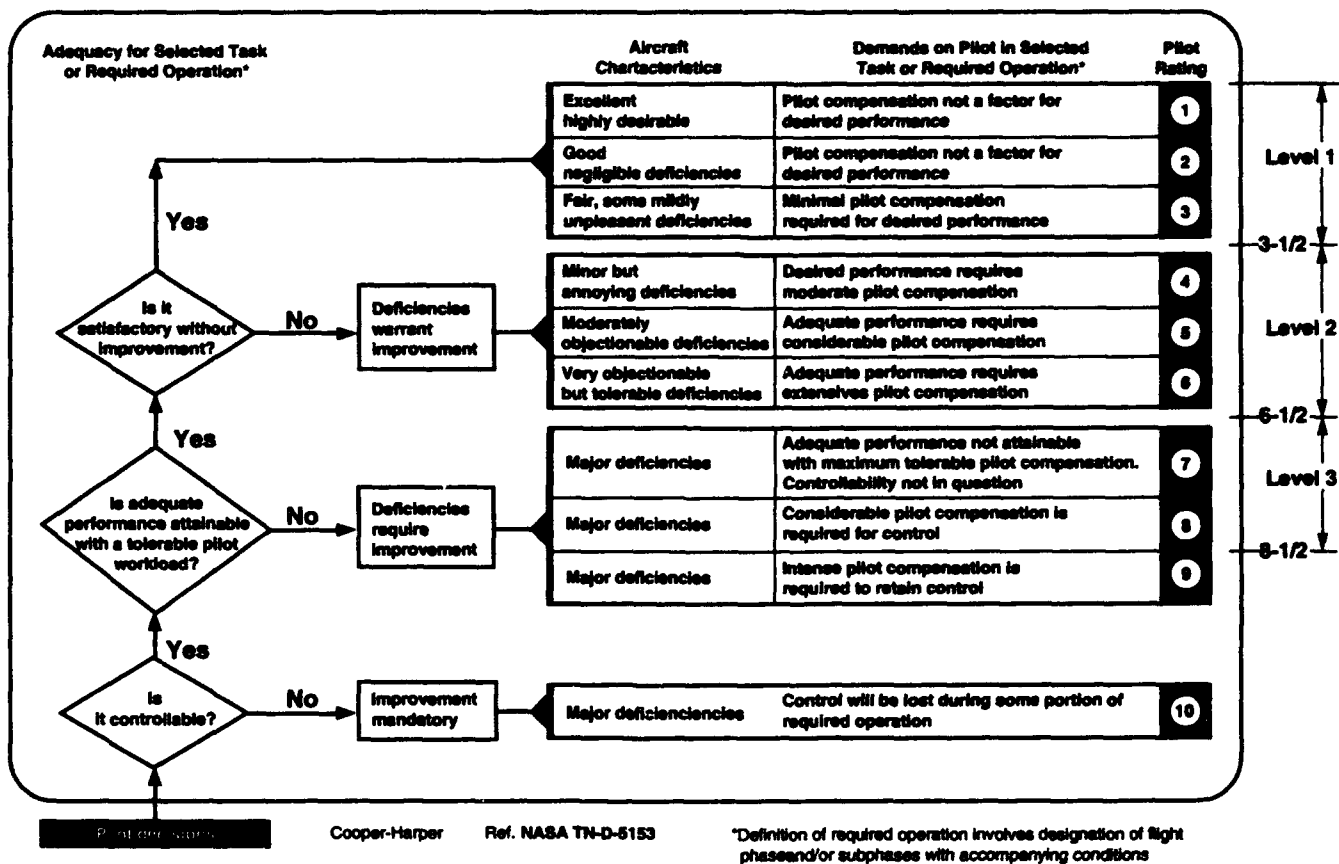
Figure 4. Cooper–Harper handling qualities rating scale.

Pilot Questionnaire

Pilot _____ Date _____ Time _____

Run No. _____ Task _____

FPS on/off? _____ CGI _____

HQR [ ]

Questions:

(1) Which axis (roll, pitch, heave) required the most compensation in the task?

(2) Was the field of view provided in the cockpit adequate throughout the task?

(3) Was scene detail adequate for performing the task?

(4) Did the monitoring of engine/rotor instruments pose any difficulty in the task?

(5) Were any engine/rotor difficulties encountered, e.g. overspeed?

(6) Did you have cyclic force trim on or off during the task?

(7) Was there any tendency for PIO in any axis in the task?

(8) Was the time specified for the completion of the task a limiting factor in your performance, e.g., could shorter completion times have been accomodated?

(9) What was the limiting factor(s) in the aggressiveness with which you were able to perform the task?

(10) In the hover-board tasks, did the control of the vehicle longitudinal position pose any problems?

(11) Was the cockpit vibration adequate for the task? Was the vibration a help? A hinderance?

(a)

Figure 5. Pilot questionnaire.

(12) Were there noticeable differences in motion cues between flight and simulator? Do you feel that the differences affected your performance/workload to accomplish the task?

(13) Were there noticeable differences in controller characteristics between simulator and flight in this task, e.g., force-feel characteristics?

(14) Were there noticeable differences in basic vehicle response characteristics between flight vehicle and simulator in this task? Did these differences affect your ability to do the task? Performance/workload?

(15) Were there noticeable differences in your control technique between simulator and flight in this task?

(16) Was the simulated noise environment satisfactory?

(17) What do you think is necessary to improve the fidelity of simulation for this task?

(18) Rate the following on a scale from 1 = poor to 5 = excellent

motion cues _____ visual cues _____

controllers: cyclic _____ coll _____ ped _____

vehicle response characteristics _____

task _____

(b)

Figure 5. Pilot questionnaire (Concluded).
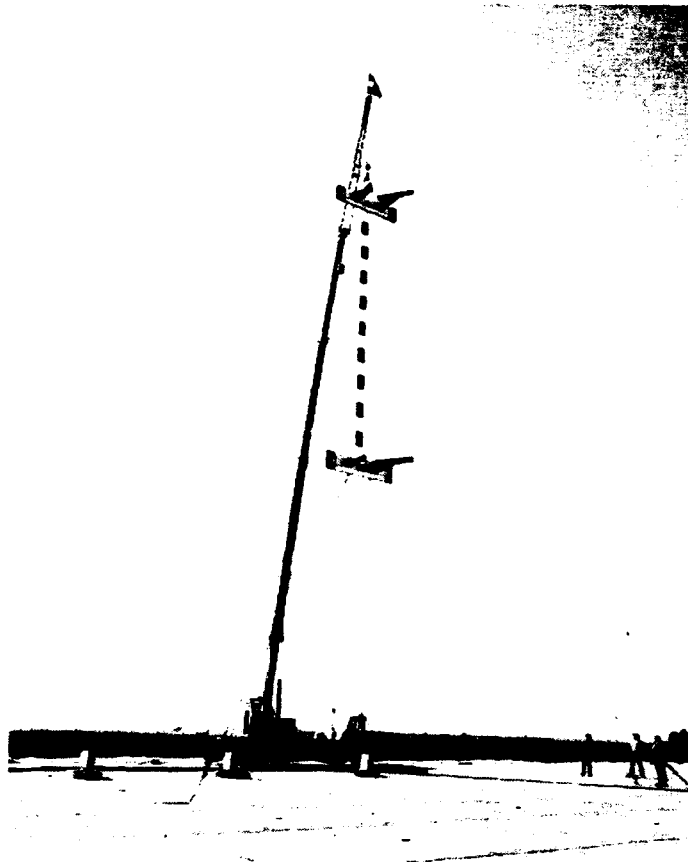
Figure 6. Hover board—vertical position.

Figure 7. Hover board—horizontal position.
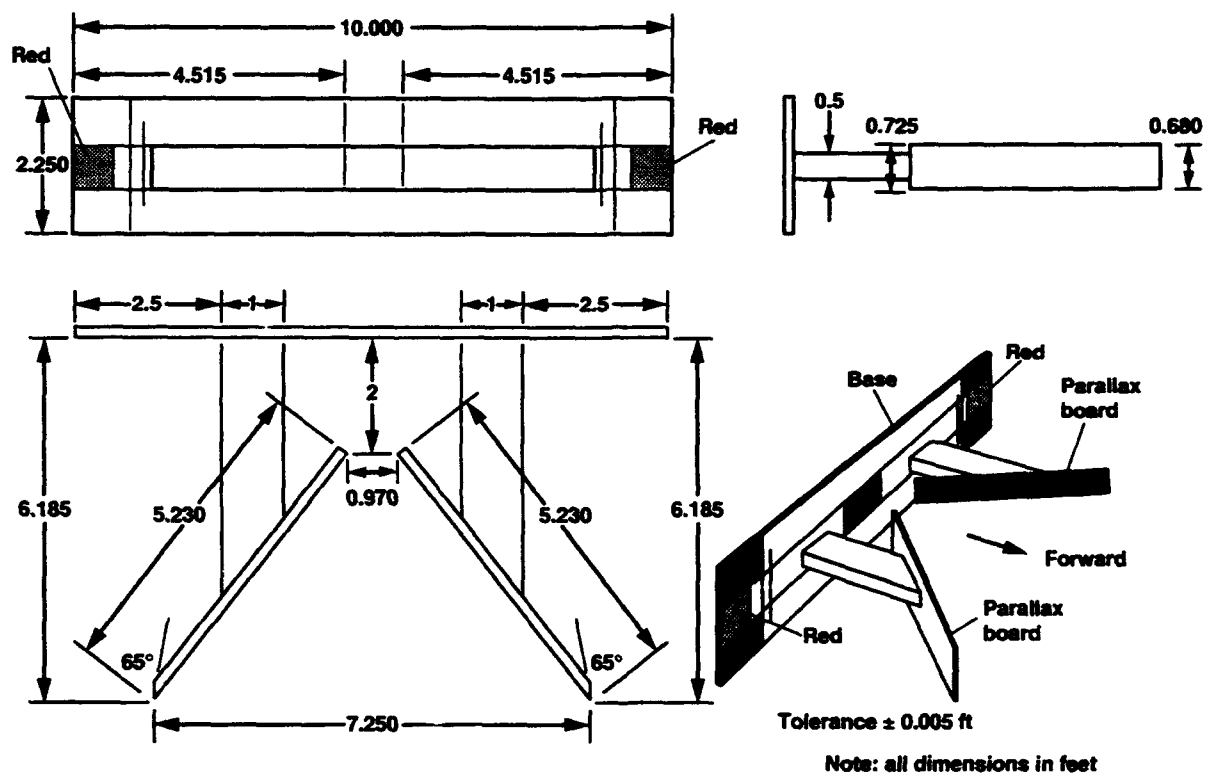
Figure 8. Hover board optical sight target.

Date and flights	Temp (°F)	Average wind speed (knots)	wind direction (deg)
July 11, 1989			
Bob-up			
Dash / quick-stop			
Flight 16	68	6.07 σ = 1.37	320
Flight 17	71	8.00 σ = 1.75	340
July 12, 1989			
Bob-up			
Dash / quick-stop			
Flight 18	62	5.97 σ = 1.21	340
Flight 19		~8.00*	350
July 18, 1989			
Bob-up			
Dash / quick-stop			
Flight 22	75	5.22 σ = 1.32	040
Flight 23	78	~5.50*	030
July 19, 1989			
Side step			
Flight 24	70	4.94 σ = 1.40	000

Data recorded:
NASA Ames Flight Test Facility/NALF Crows Landing
Elevation 141 feet above sea level
* Values taken from hourly averages recorded at
  NASA Crows weather station

Figure 9. Flight test atmospheric conditions.

'B' rigid blades – Flapping and lagging
Rotor speed degree-of-freedom
Lag damper
Blade element aero. ($\alpha = \pm 180°$, M = 0–1.0)
Yawed flow
Momentum inflow with harmonic distribution

Tail rotor (Bailey)

Rotor downwash
on empennage
and tail rotor

Rotor downwash
on fuselage

Control system
Sticks
Mixing
AFCS
Servos

Fuselage wake
on empennage

Rigid fuselage = 6 degrees-of-freedom
six component aero $\alpha, \beta = \pm 90°$

Empennage
aerodynamics
Lift
Drag
Sideforce
$\left.\right\}$ $\alpha, \beta = \pm 90°$

Figure 10. Gen Hel mathematical model components.

49
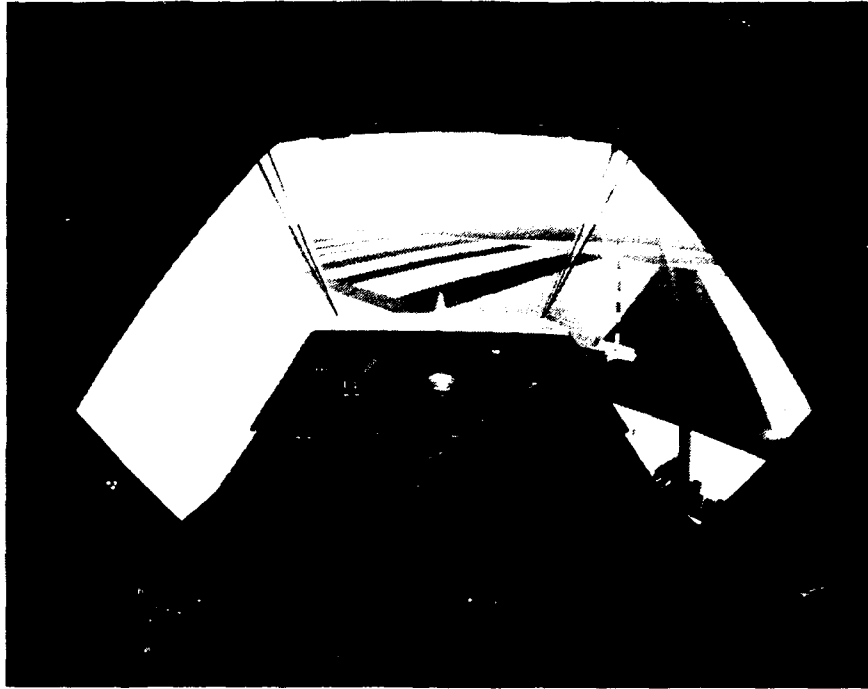
Figure 11. F-CAB field of view in simulator.

Figure 12. N-CAB field of view in simulator.
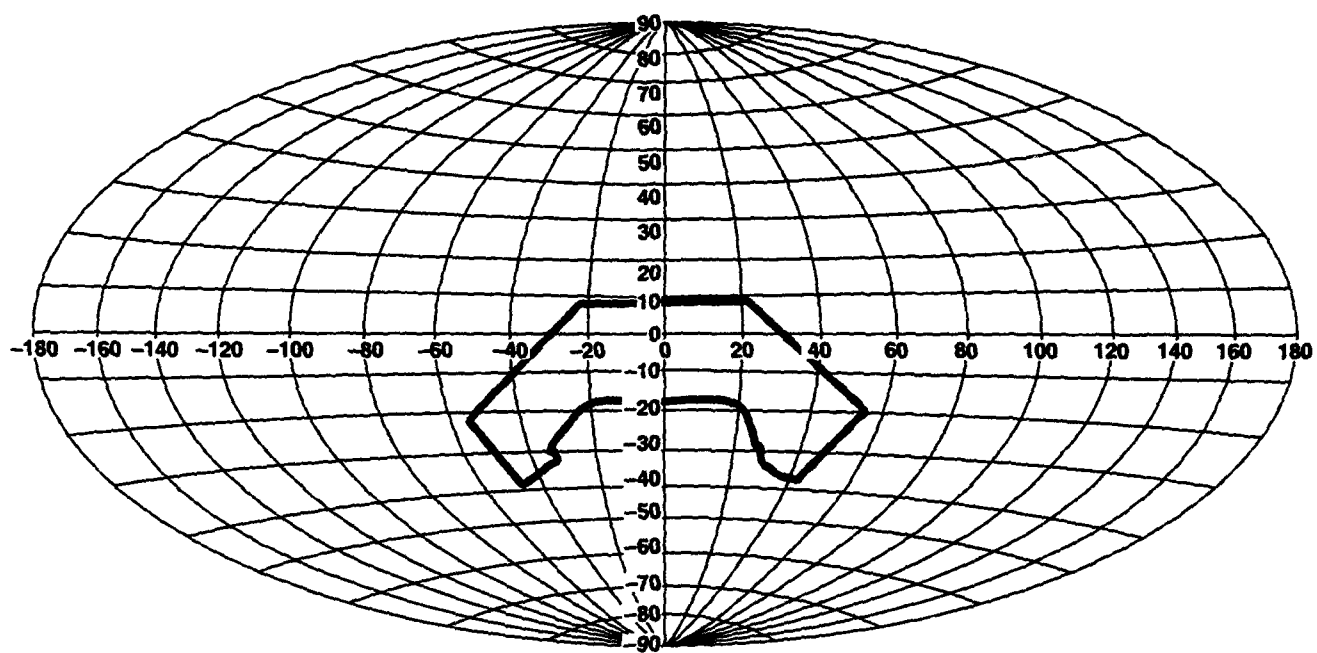
Data measured June 1990

Figure 13. Field of view from F-CAB.
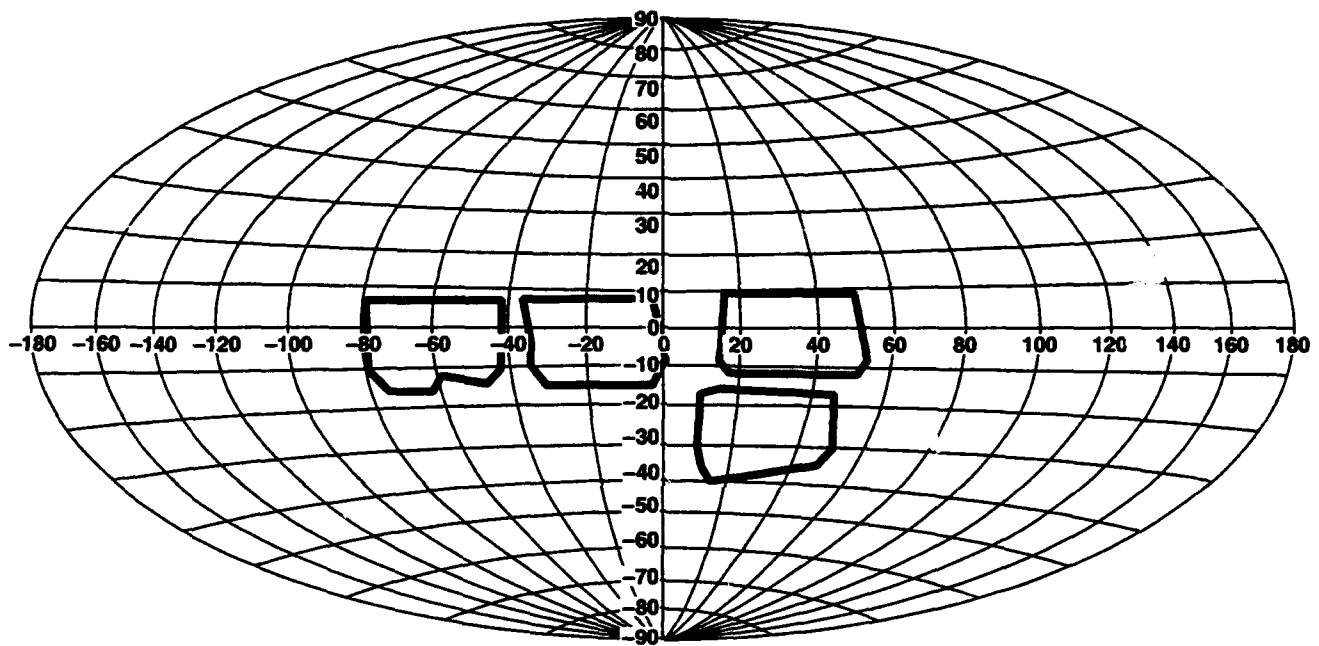
Data measured July 1990

Figure 14. Field of view from N-CAB.

Figure 15. Field of view from UH-60A.
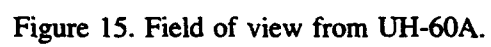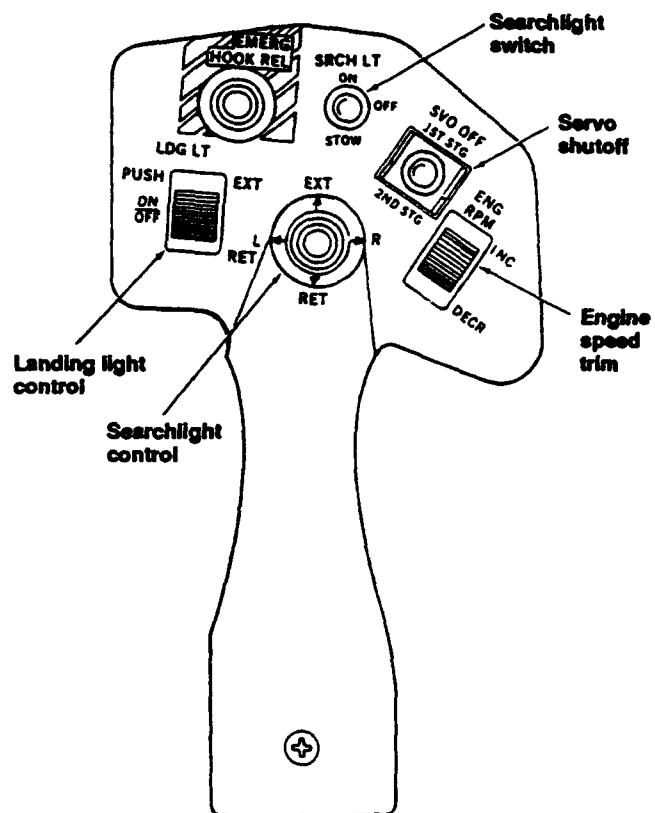
Figure 16. Collective grip.
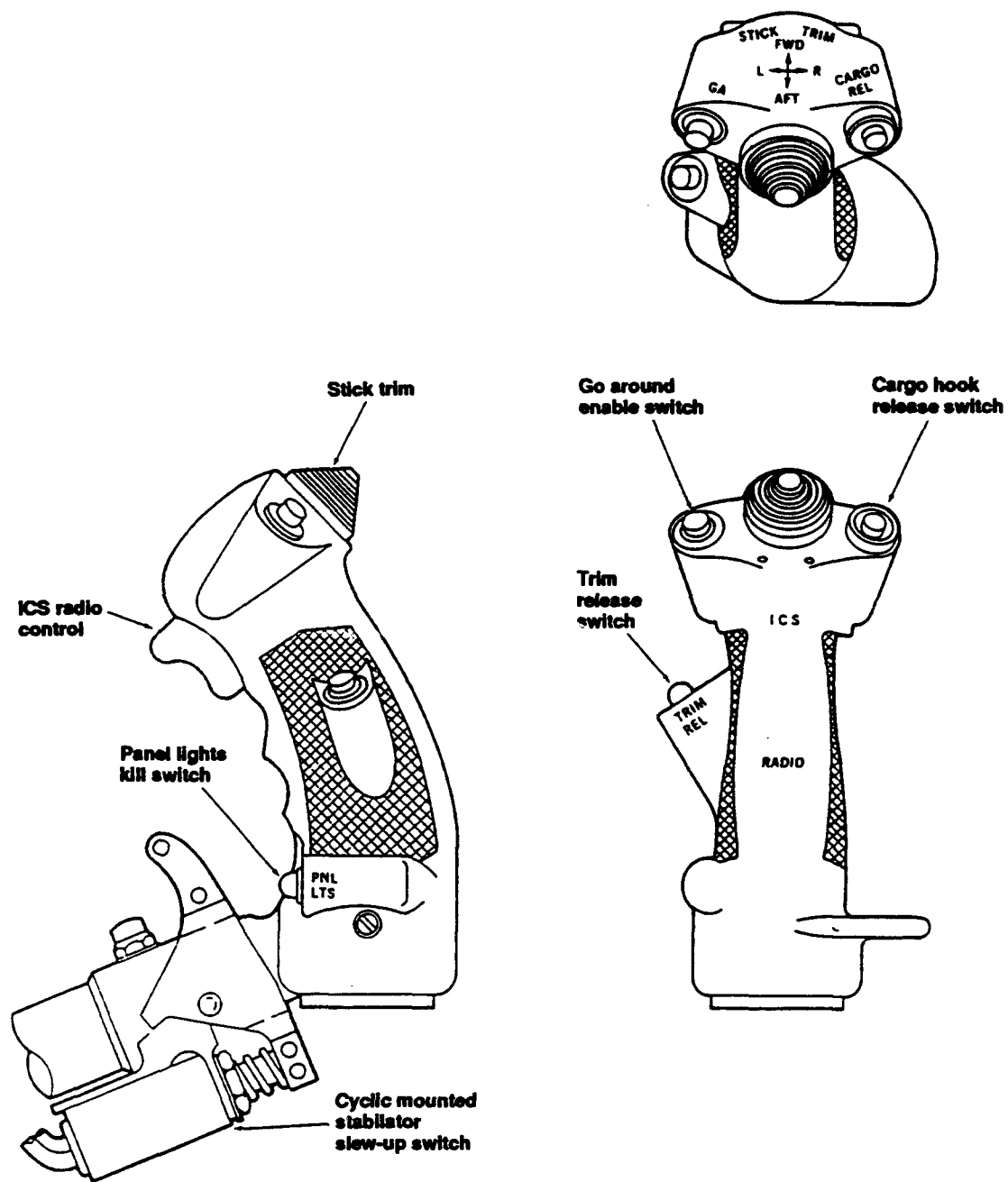
Figure 17. Cyclic grip.
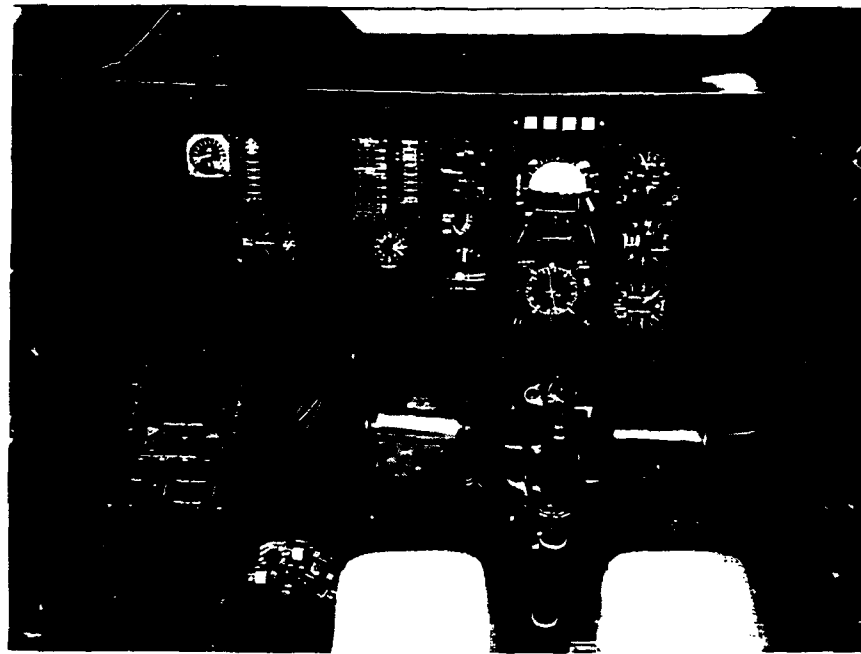
(a) Aircraft.
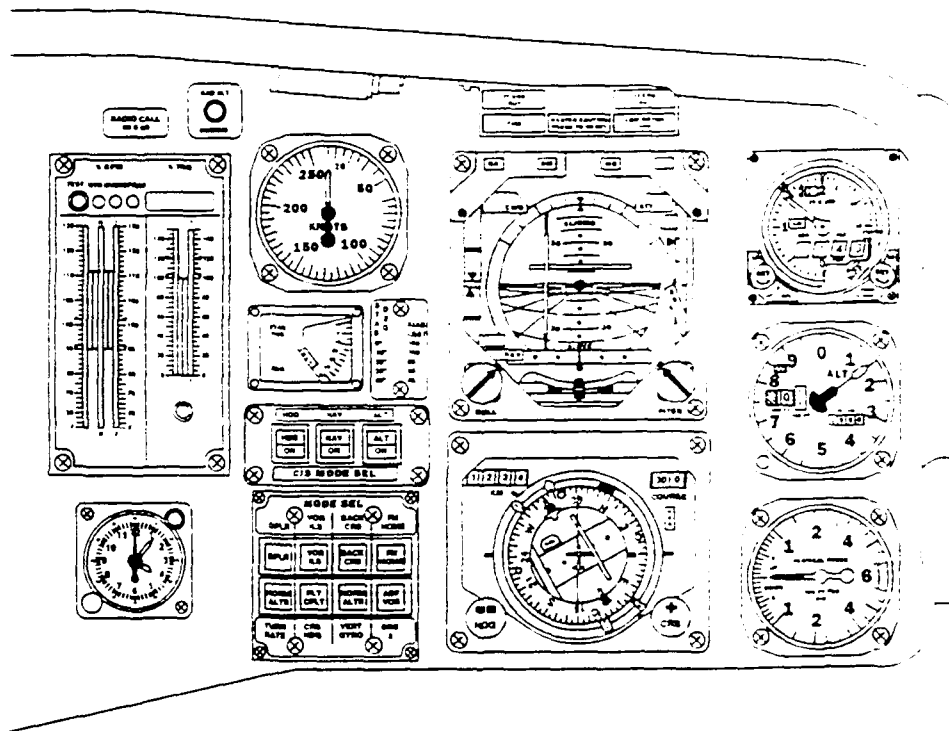
(b) Simulator.

Figure 18. Instrument panel layout.
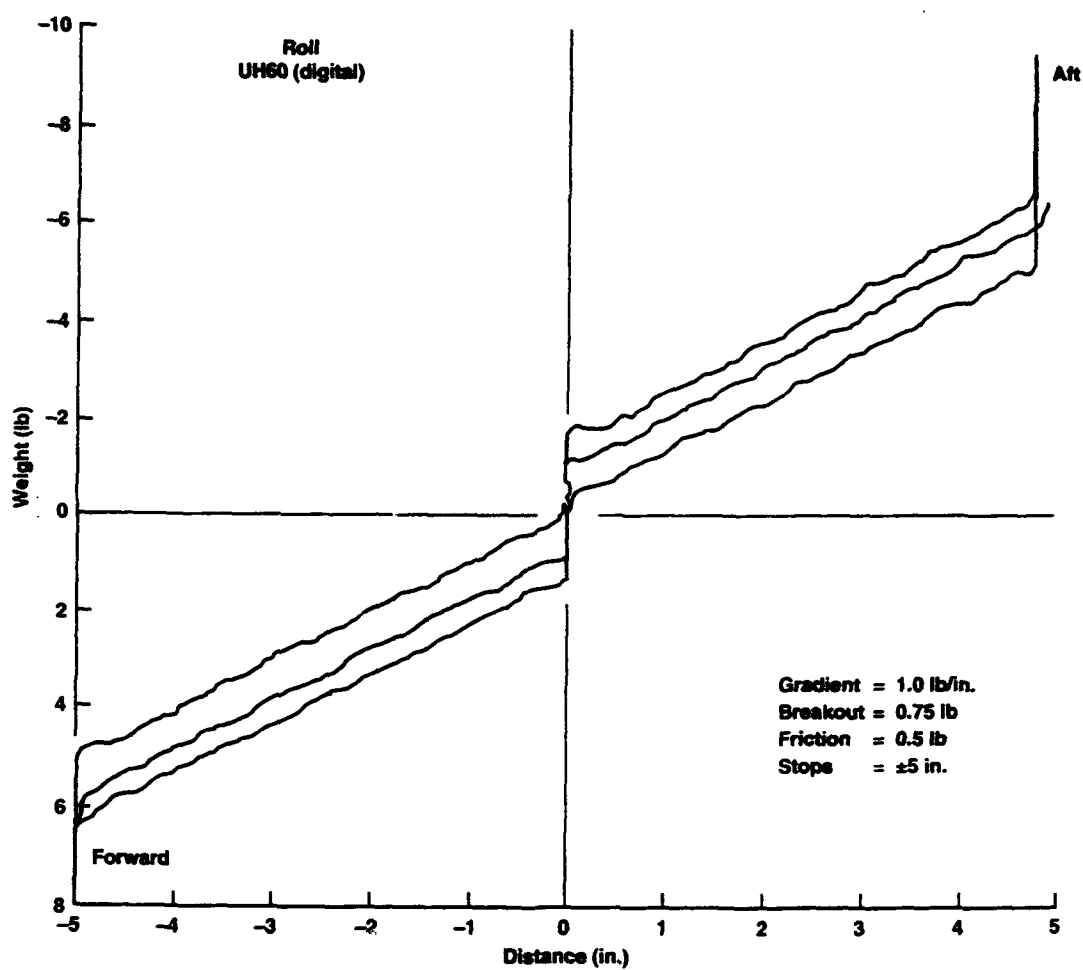
Figure 19. Calibration curves for controller loaders.
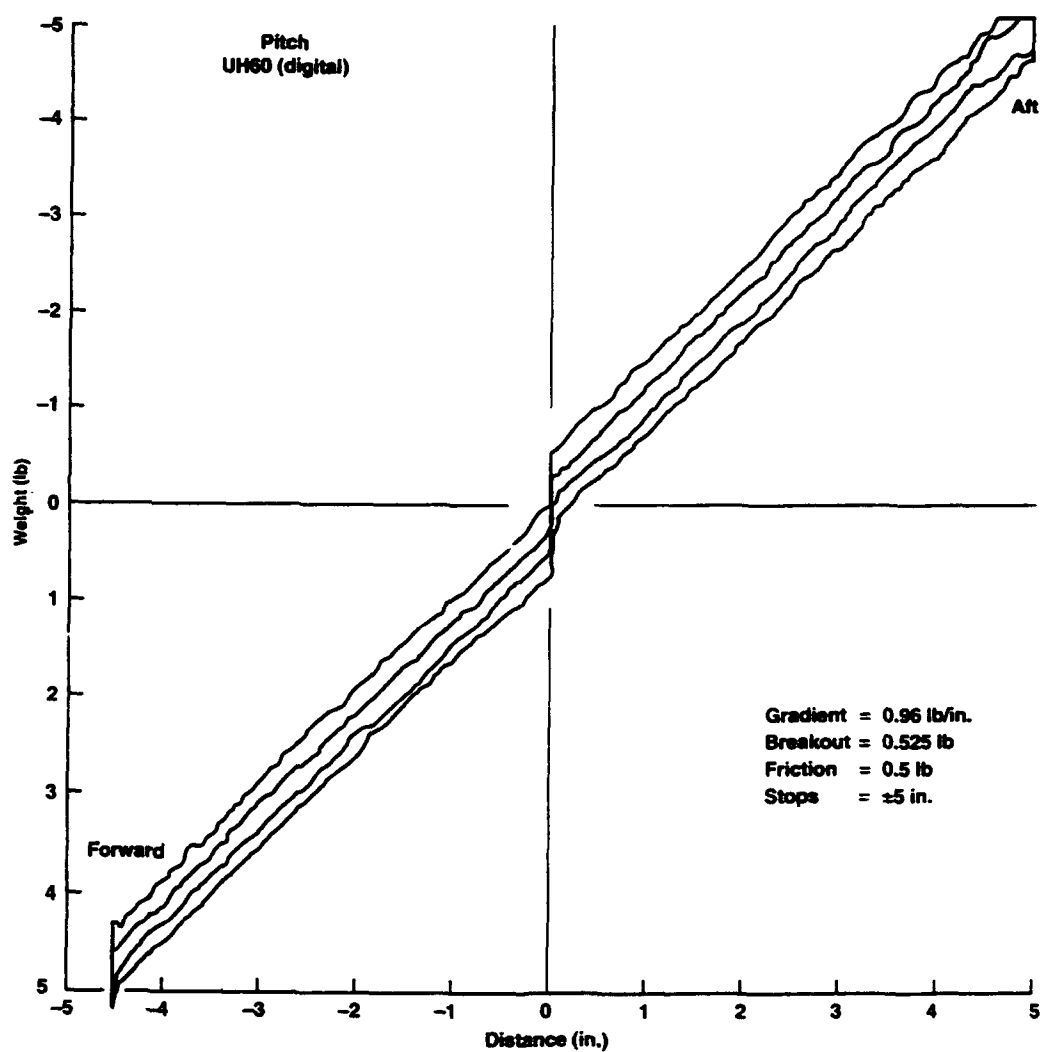
Figure 19. Calibration curves for controller loaders (Continued).
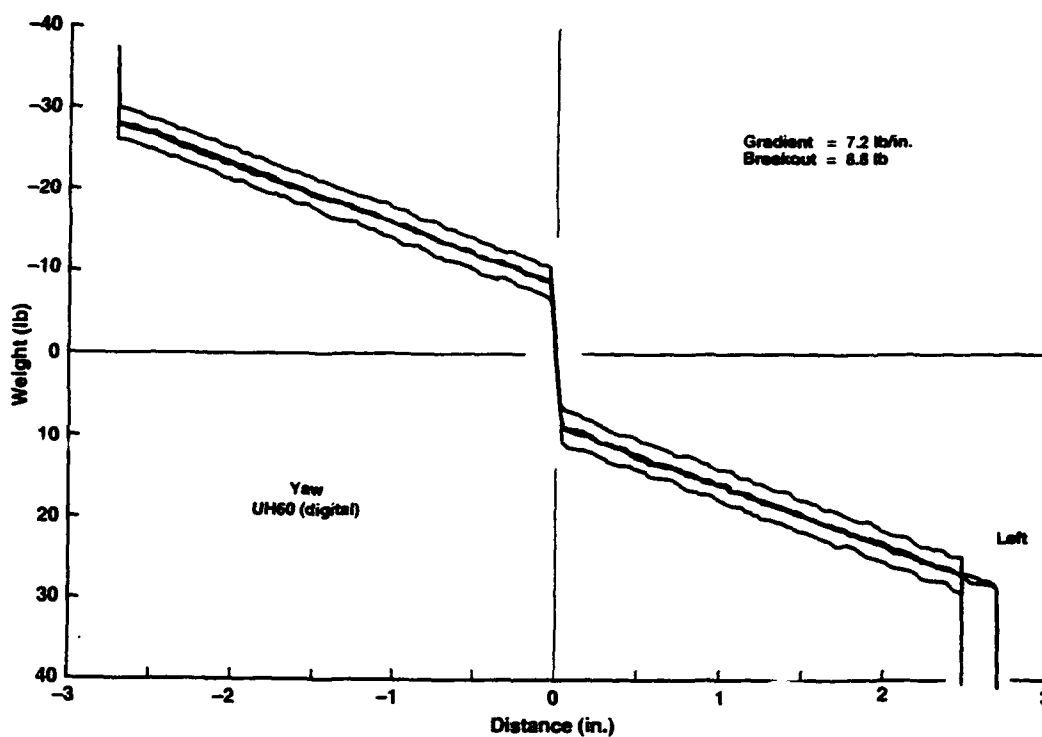
Figure 19. Calibration curves for controller loaders (Continued).
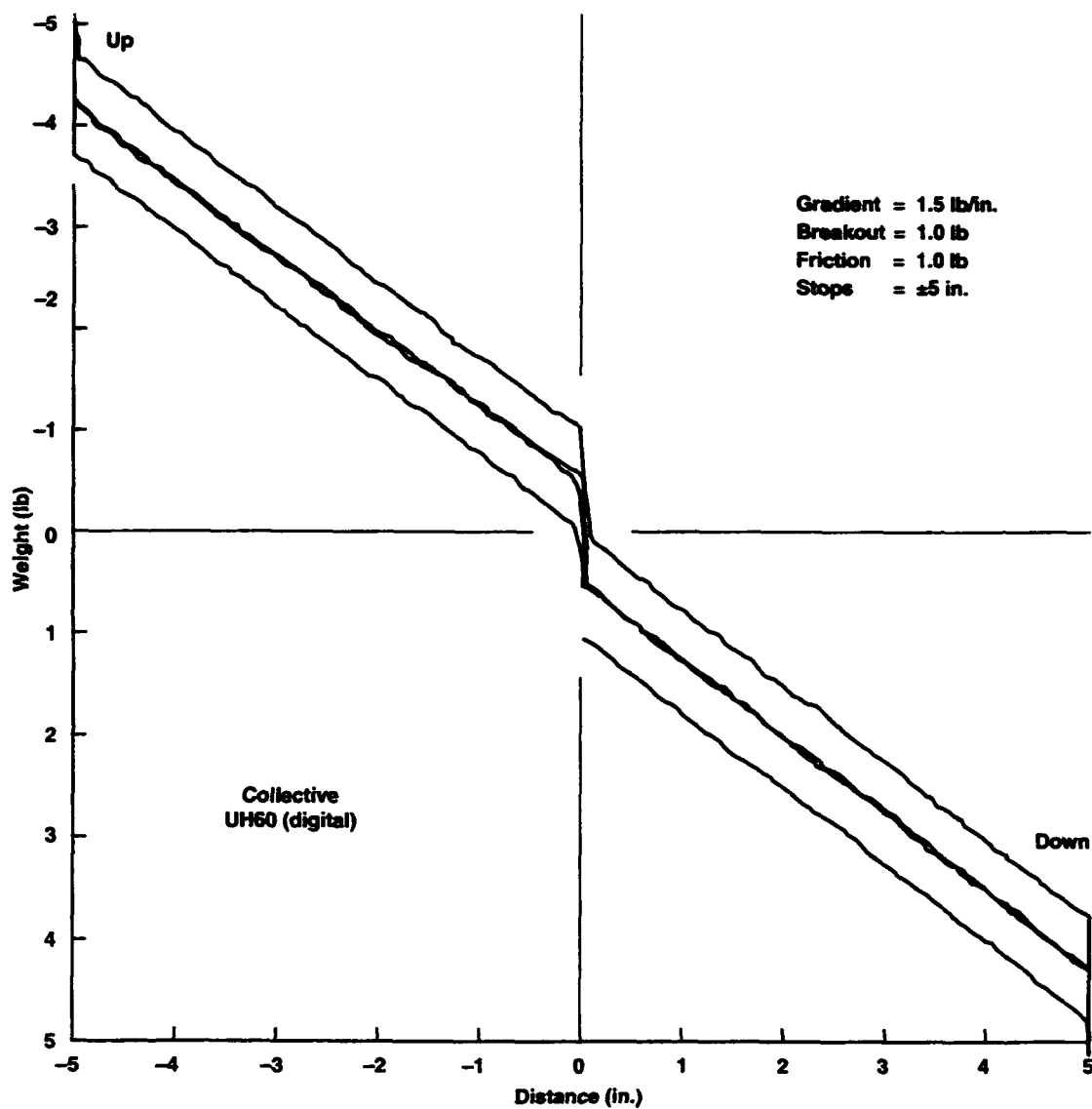
Figure 19. Calibration curves for controller loaders (Concluded).

61

	Pitch force	Roll force	Yaw force	Collective force
Initial conditions				
Gradient	0.0	0.0	0.0	0.0
Breakout	0.0	0.0	0.0	0.0
Friction	0.75	0.6	0.5	3.74
Damping	0.0	0.0	6.0	—
Operating conditions				
Gradient	1.0 lb/in.	1.0 lb/in.	7.2 lb/in.	1.5 lb/in.
Breakout	0.525 lb	0.75 lb	8.8 lb	1.0 lb
Friction	0.5	0.5	0.5 lb	0.0
Damping	0.2 lb/in./sec	0.15 lb/in./sec	6.0 lb/in./sec	—
Fade-time	0.1 sec	0.1 sec	0.1 sec	0.1 sec

Figure 20. Force feel system values.

VMS Motion System Performance Limits

Degree of freedom	Displacement		Velocity		Acceleration	
	System limits	Operational limits	System limits	Operational limits	System limits	Operational limits
Longitudinal	±4 ft	±3 ft	±5 ft/sec	±4 ft/sec	±16 ft/sec/sec	±10 ft/sec/sec
Lateral	±20 ft	±15 ft	±8 ft/sec	±8 ft/sec	±13 ft/sec/sec	±13 ft/sec/sec
Vertical	±30 ft	±22 ft	±16 ft/sec	±15 ft/sec	±22 ft/sec/sec	±22 ft/sec/sec
Roll	±0.31 rad	±0.24 rad	±0.9 rad/sec	±0.7 rad/sec	±4 rad/sec/sec	±2 rad/sec/sec
Pitch	±0.31 rad	±0.24 rad	±0.9 rad/sec	±0.7 rad/sec	±4 rad/sec/sec	±2 rad/sec/sec
Yaw	±0.42 rad	±0.34 rad	±0.9 rad/sec	±0.8 rad/sec	±4 rad/sec/sec	±2 rad/sec/sec
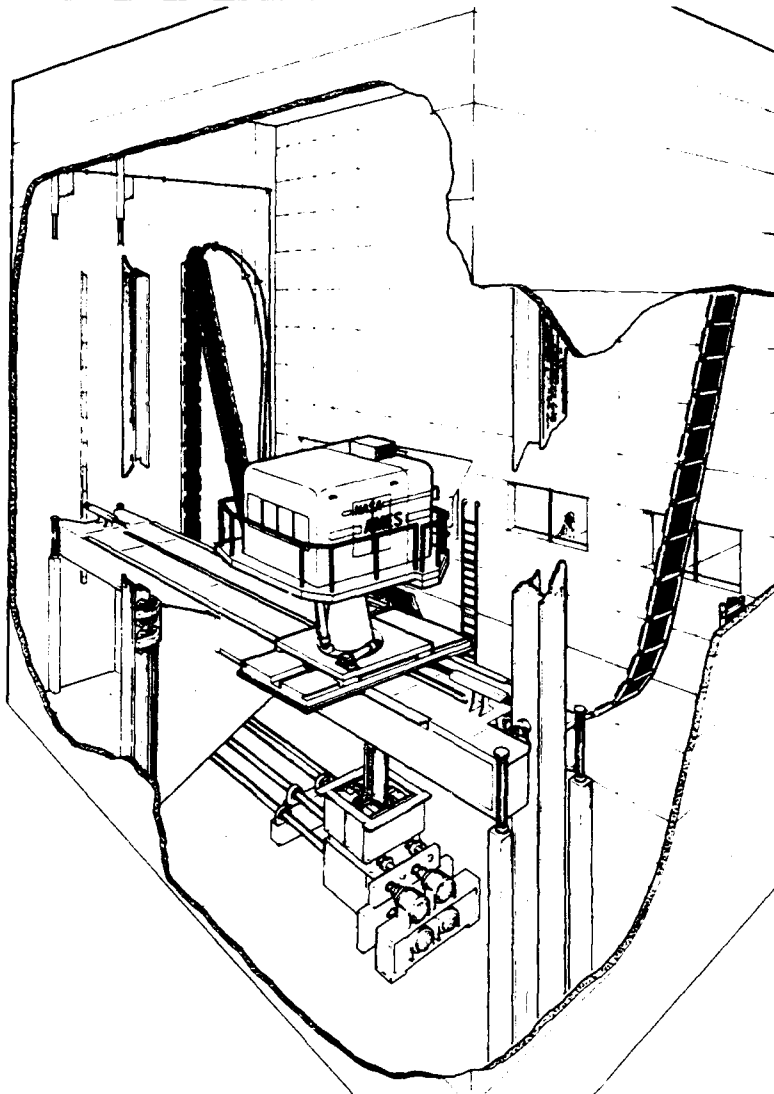
Figure 21. Vertical Motion Simulator.

63

Figure 22. Vertical Motion Simulator constraint logic.
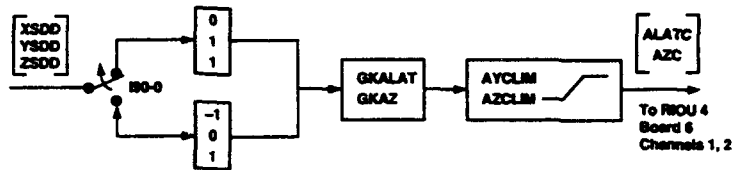
Acceleration feed forward
Vertical axis
Lateral axis
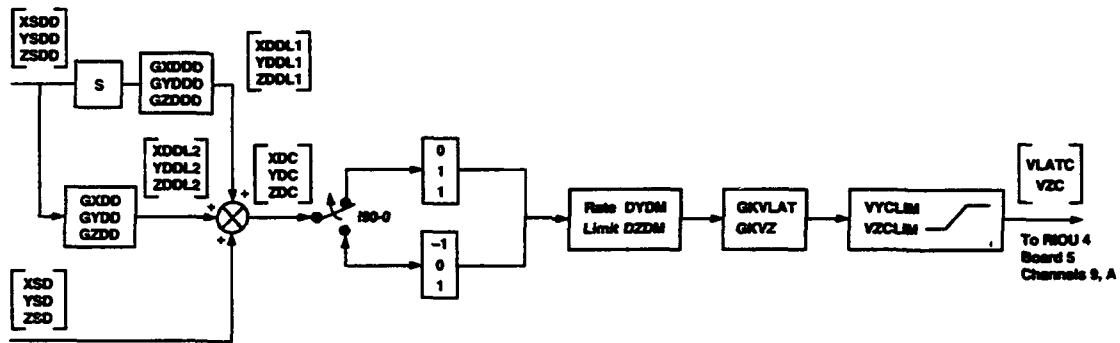
Velocity feed forward
Vertical axis
Lateral axis
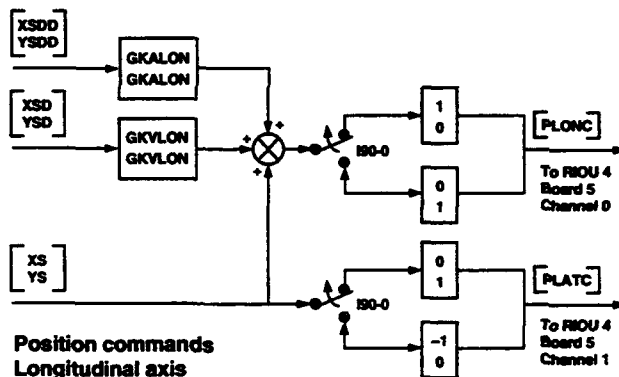
Position commands
Longitudinal axis
Lateral axis
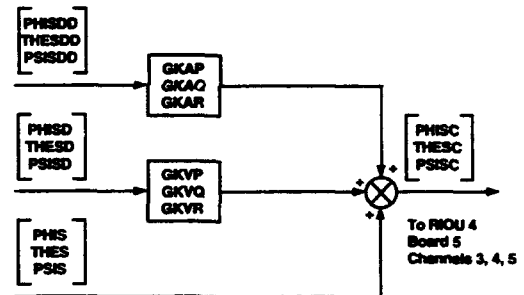
Combined feed forward
Roll axis
Pitch axis
Yaw axis

Note: The I90 switches in this diagram do not affect the vertical axis. A selection is made between lateral and longitudinal. The gains and limits used are determined by the drive axis rather than the aircraft axis. For example, in the acceleration feed forward either YSDD will be multiplied by GKALAT (I90-0) or XSDD will be multiplied by –GKALAT (I90-1), the result limited to AYCLIM and stored in ALATC.

Position command
Vertical axis

(b)

Figure 22. Vertical Motion Simulator constraint logic (Concluded).

65

Motion System parameters		
Slow airspeed < 15 knots		
GPS	roll throughput gain	0.30
GQS	pitch throughput gain	0.50
GRS	yaw throughput gain	0.50
OMEGPS	roll high-pass break frequency	0.70
OMEGQS	pitch high-pass break frequency	0.70
OMEGRS	yaw high-pass break frequency	0.50
GXS	longitudinal throughput gain	0.40
GYS	lateral throughput gain	0.80
GZS	vertical throughput gain	0.80
OMEGXS	longitudinal high-pass break frequency	1.50
OMEGYS	lateral high-pass break frequency	0.60
OMEGZS	vertical high-pass break frequency	0.30
GPYS	roll/lateral residual tilt throughput gain	0.60
GQXS	pitch/longitudinal residual tilt throughput gain	0.60
OMEPRS	roll residual tilt low-pass break frequency	3.00
OMEQRS	pitch residual tilt low-pass break frequency	3.00
Fast airspeed > 60 knots		
GPF	roll throughput gain	0.35
GQF	pitch throughput gain	0.50
GRF	yaw throughput gain	0.35
OMEGPF	roll high-pass break frequency	0.85
OMEGQF	pitch high-pass break frequency	0.85
OMEGRF	yaw high-pass break frequency	0.70
GXF	longitudinal throughput gain	0.40
GYF	lateral throughput gain	0.60
GZF	vertical throughput gain	0.80
OMEGXF	longitudinal high-pass break frequency	1.50
OMEGYF	lateral high-pass break frequency	0.60
OMEGZF	vertical high-pass break frequency	1.40
GPYF	roll/lateral residual tilt throughput gain	0.60
GQXF	pitch/longitudinal residual tilt throughput gain	0.60
OMEPRF	roll residual tilt low-pass break frequency	3.00
OMEQRF	pitch residual tilt low-pass break frequency	3.00
Miscellaneous		
VSLOW	slow airspeed breakpoint	15.00
VFAST	fast airspeed breakpoint	60.00
ZETAP	roll damping ratio	0.707
ADCL	vertical lead compensation accel feedforward limit	40.00
GXQ	turn coordination gain	0.00
GYC	turn coordination gain	1.00
GKRS	turn coordination feedback gain	0.50
GKVLAT	feedforward rate gain for RSMG – lateral	–1.70
GKALAT	feedforward acceleration gain for RSMG – lateral	0.13

Figure 23. Motion washout values.

66
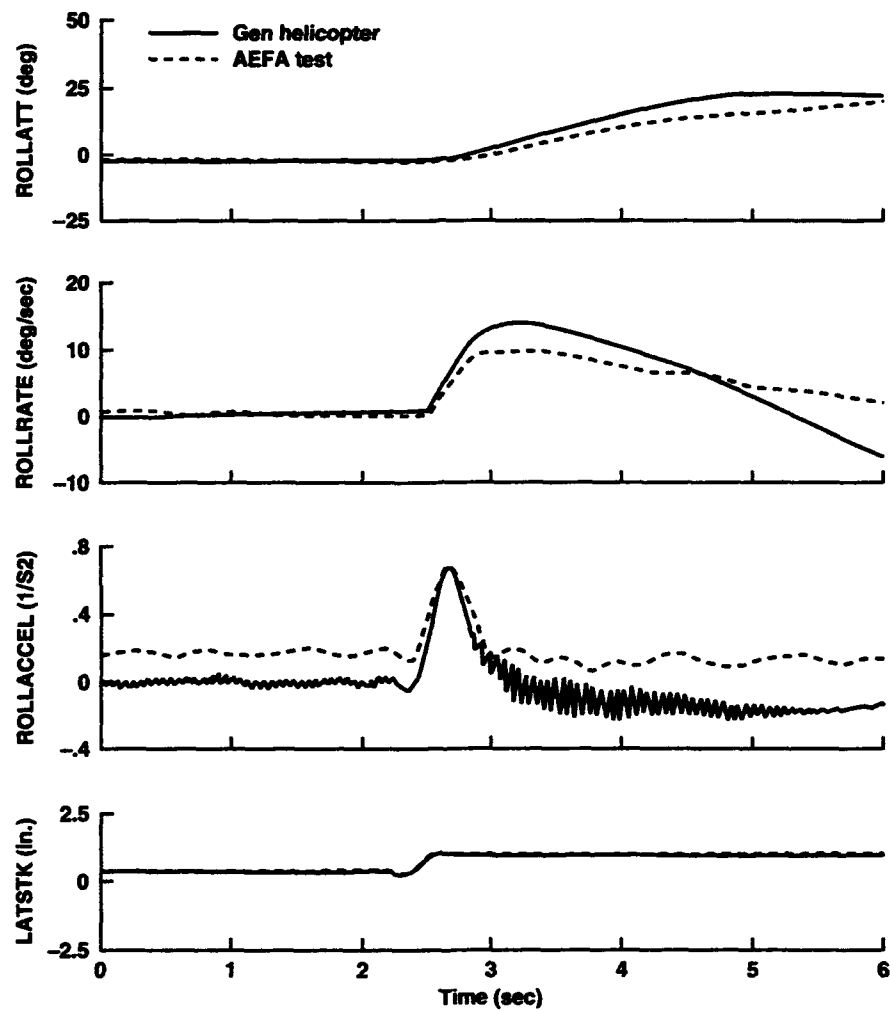
Figure 24. Model-to-flight sample data.
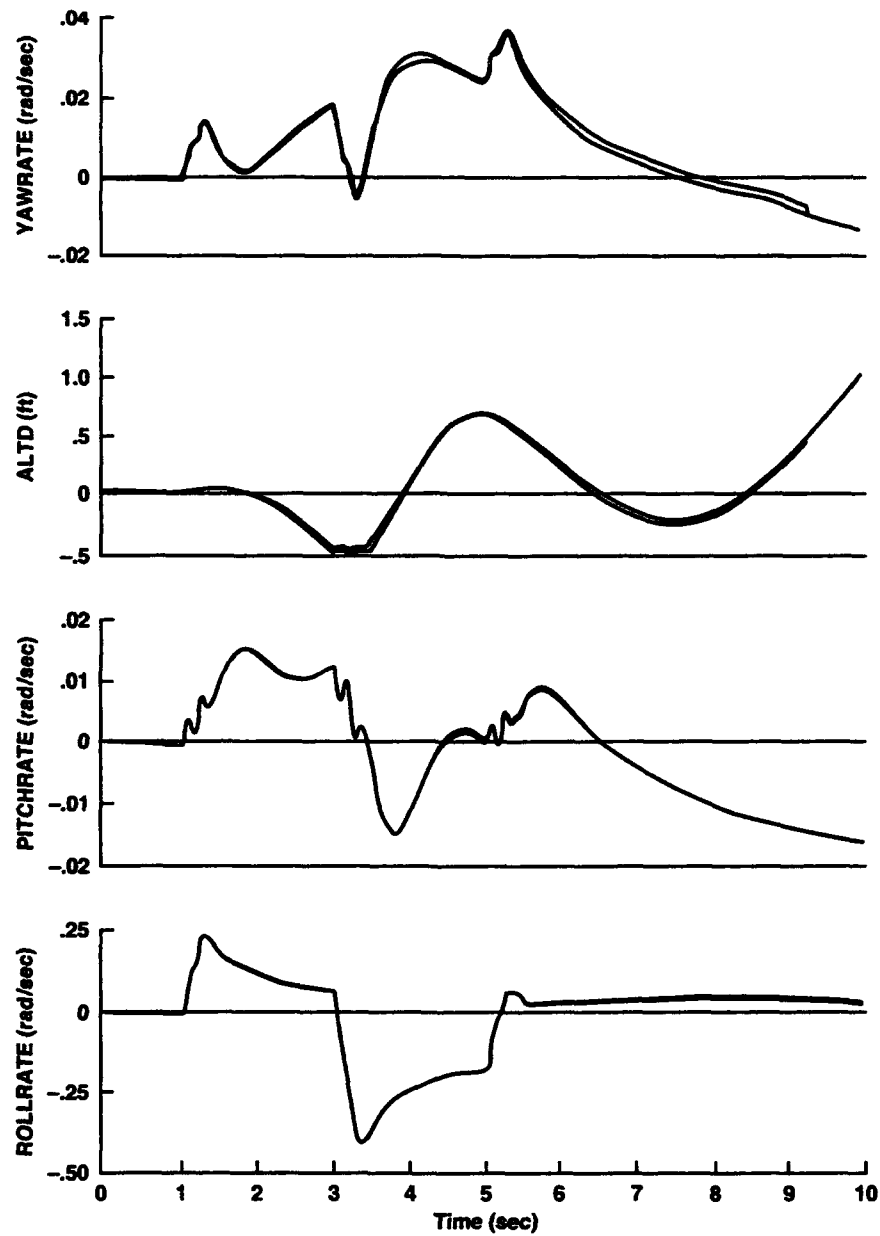
Figure 25. Daily check case data.
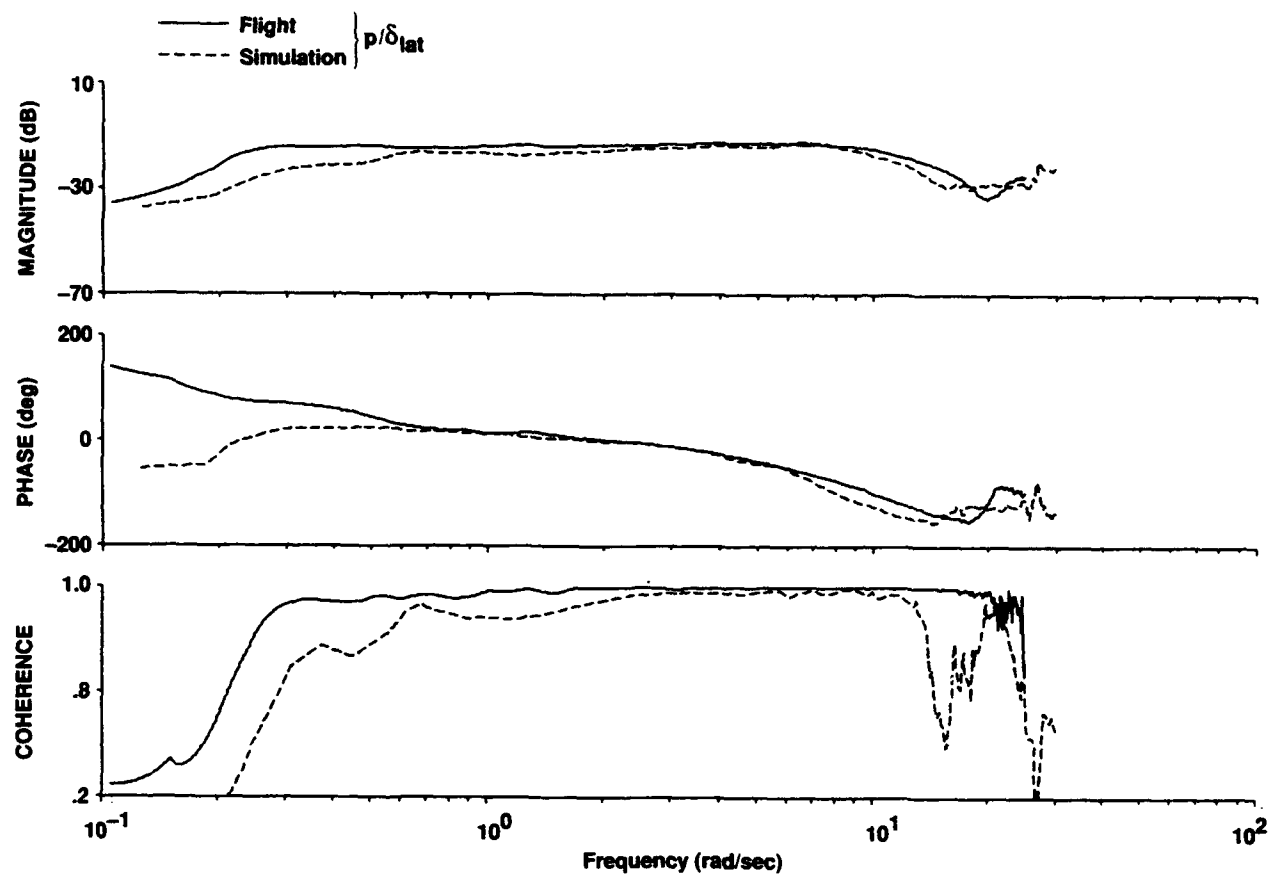
Figure 26. Aircraft/math model frequency sweep data—p/δ_{lat}.
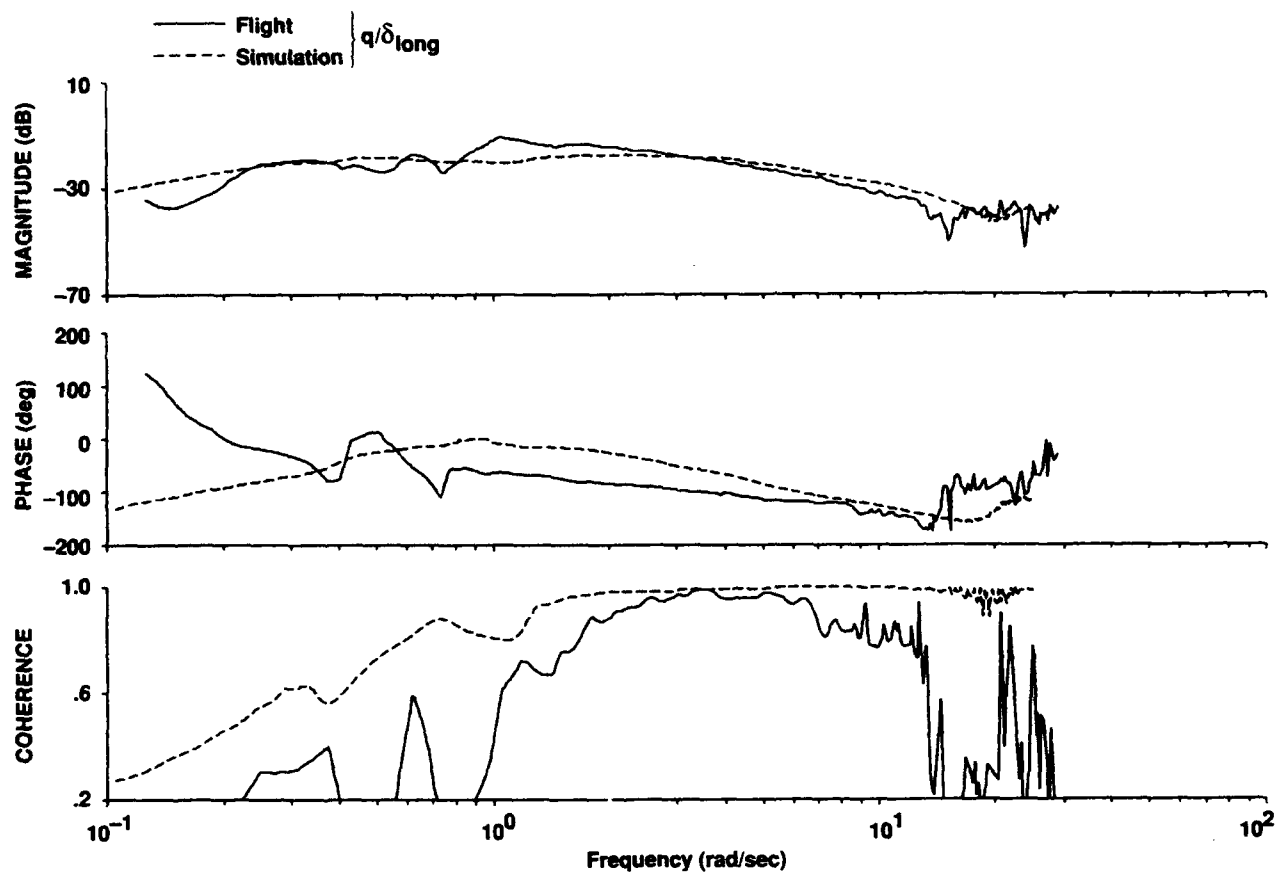
Figure 27. Aircraft/math model frequency sweep data—q/δ_{long}.
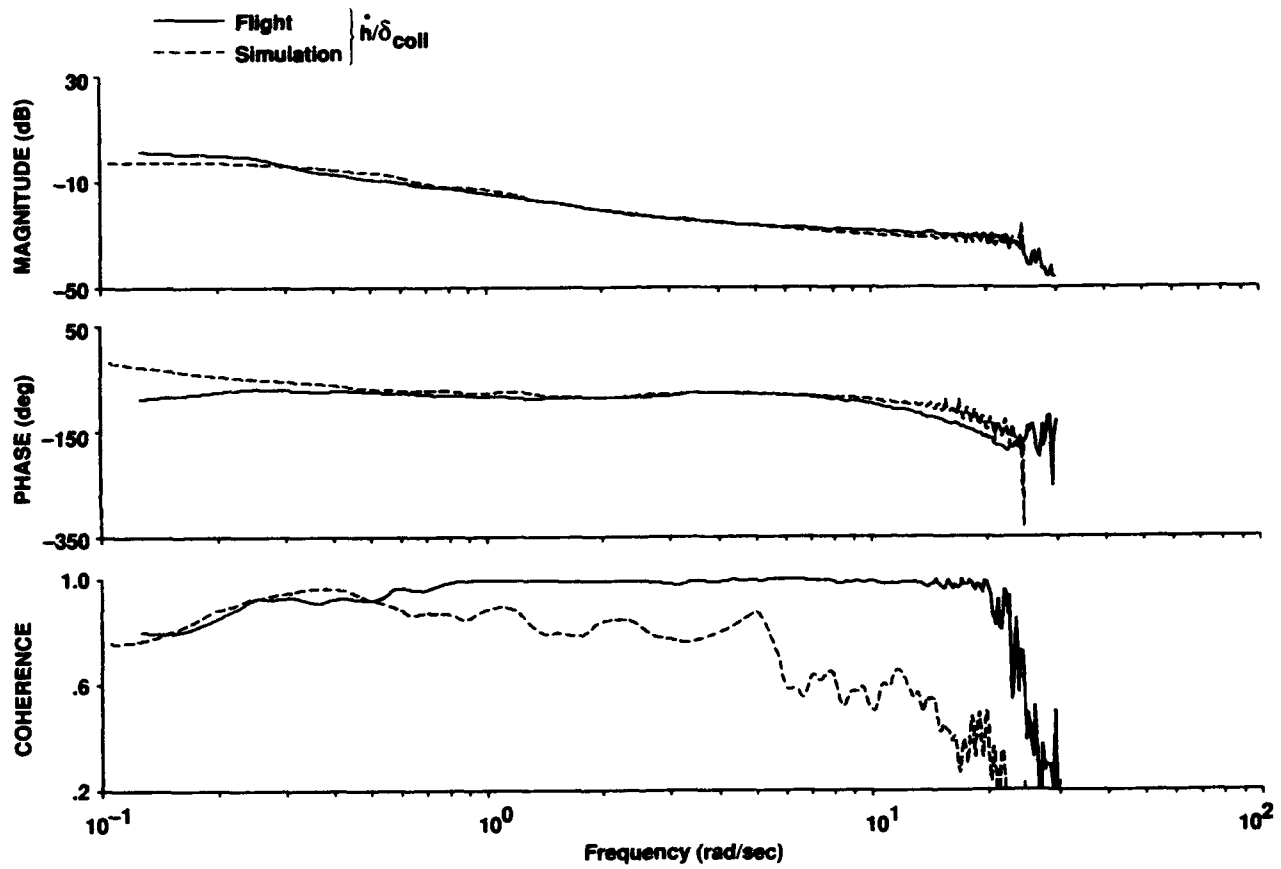
Figure 28. Aircraft/math model frequency sweep data—$\dot{h}/\delta_{coll}$.
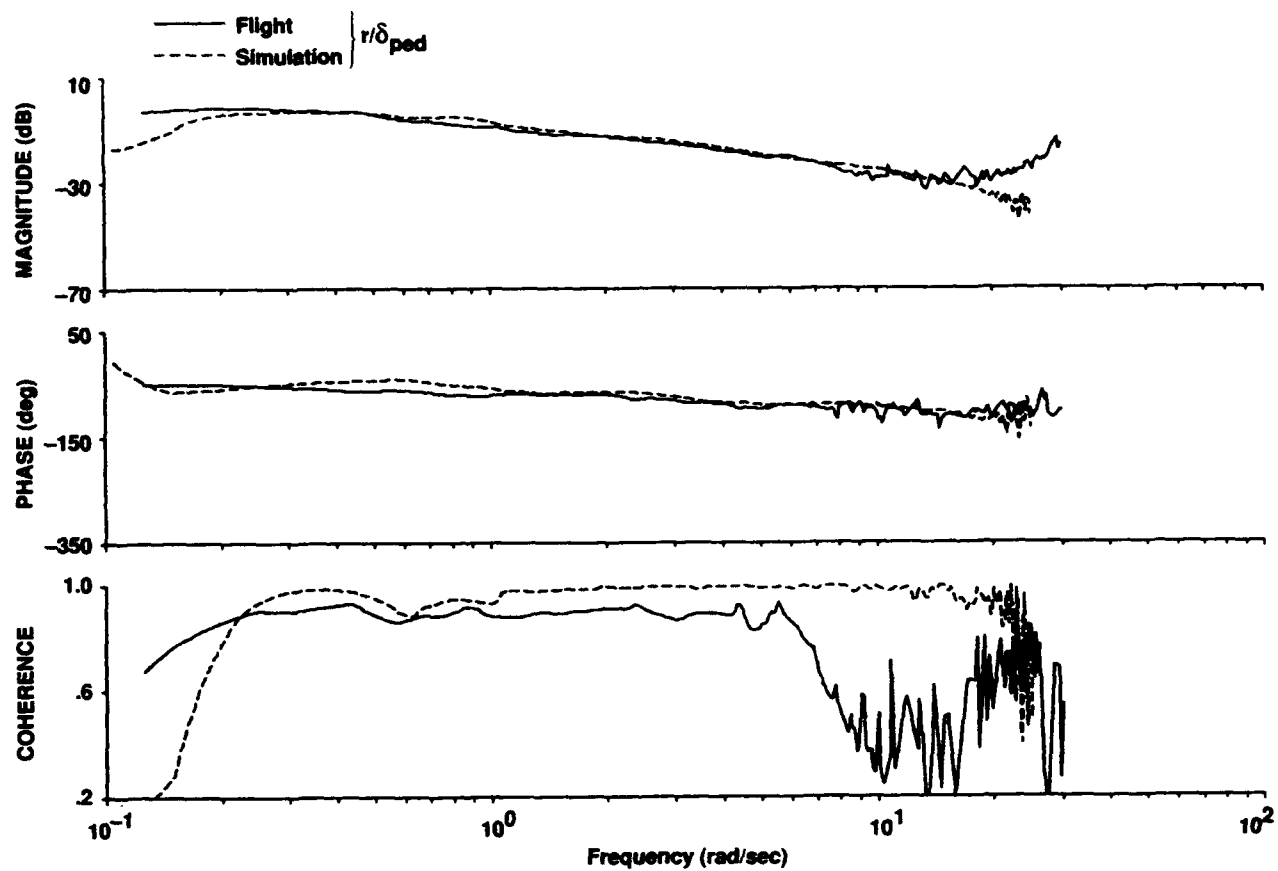
Figure 29. Aircraft/math model frequency sweep data—r/δ_{ped}.

Pilot input	Source	Value	m/sec
W_4	A/D	ρ_4	8.0
W_9	D/D$_{in}$	ρ_9	2.0
W_0	Model/sub-cycle	ρ_0	−6.7
W_1	Delay/sub-cycle	ρ_1	6.7
W_2	Conversion	ρ_2	6.7
W_5	CGI compression	ρ_5	−83.3
W_{10}	D/D$_{out}$	ρ_{10}	2.0
W_3	D/A	ρ_3	10.0
W_6	D/D$_{cgi}$	ρ_6	2.0
W_7	CGI asymmetric	ρ_7	–
W_8	CGI pipeline	ρ_8	83.3
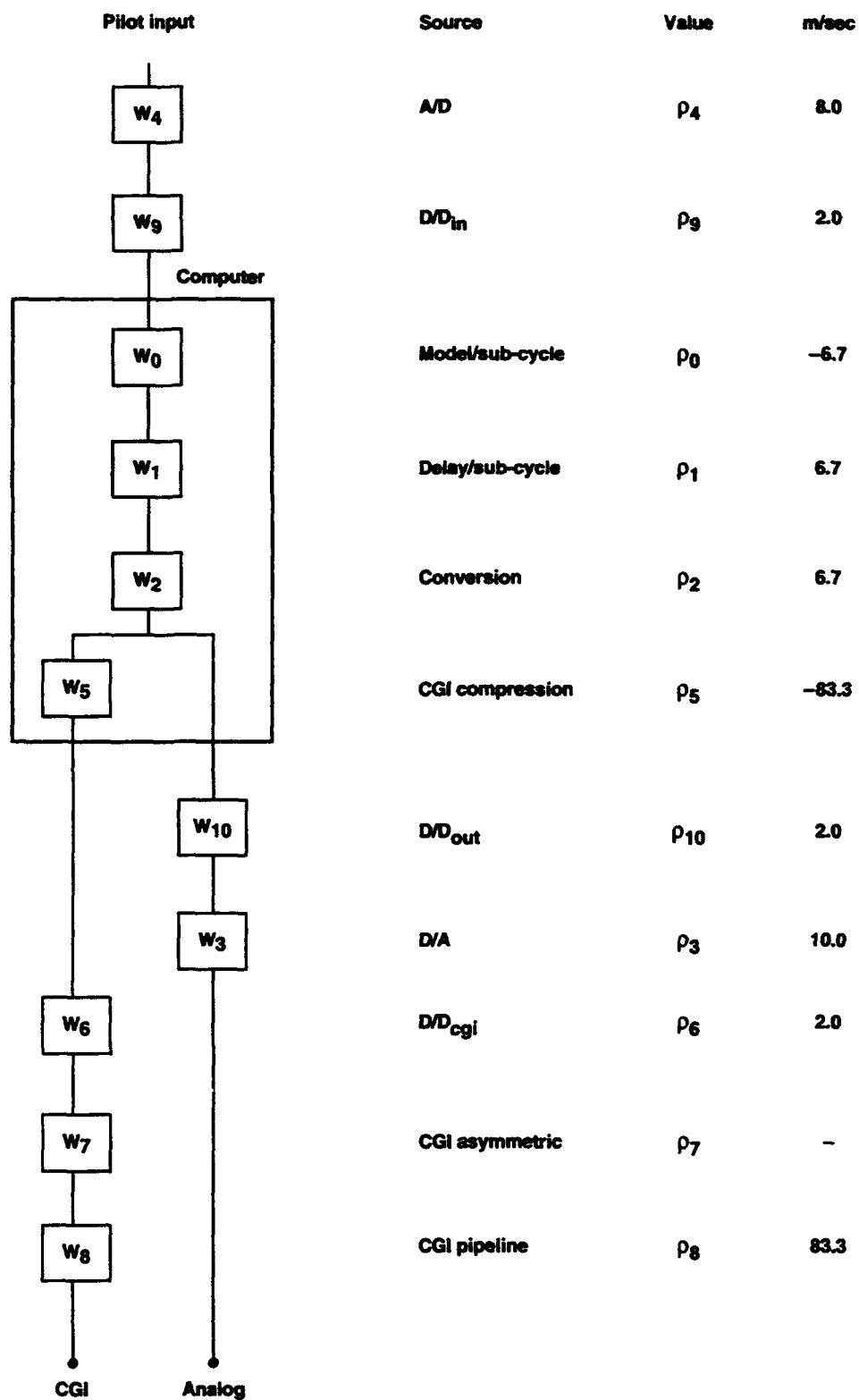
Figure 30. Computer sequence time delay.
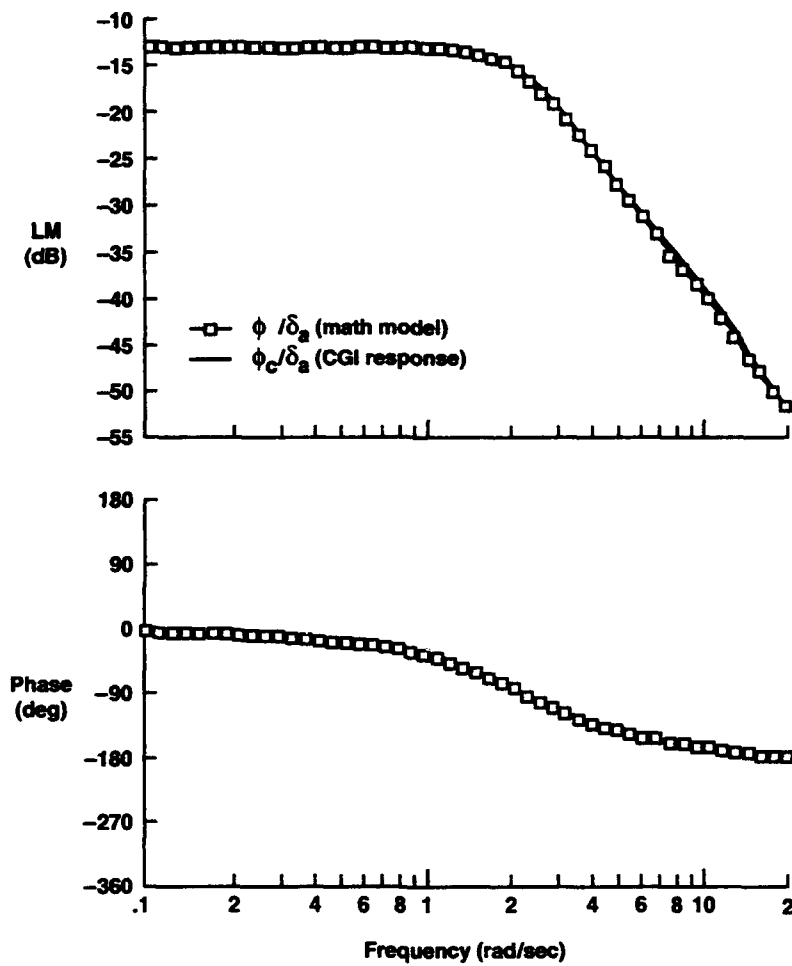
Figure 31. Simulator model/visual frequency sweep data (ref. 25).

74
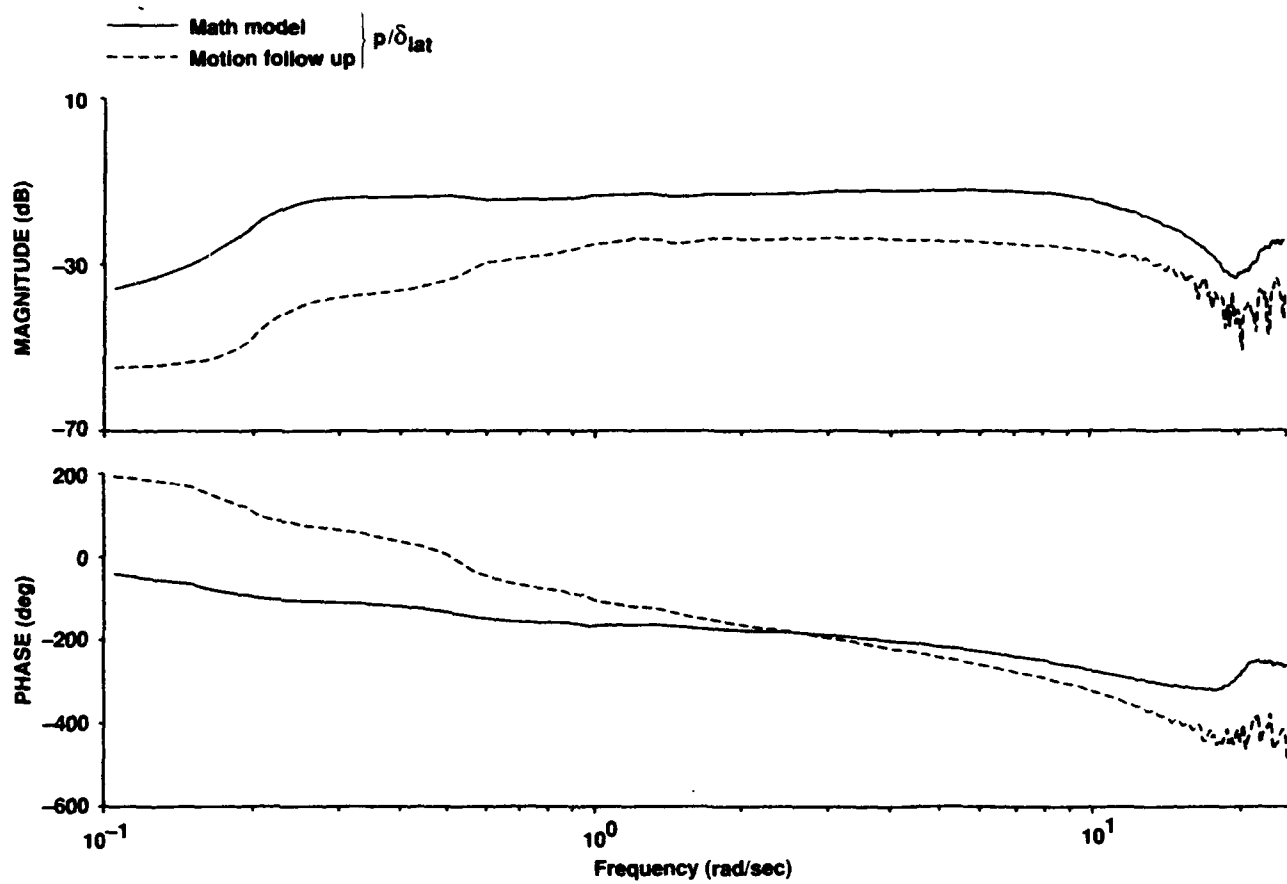
Figure 32. Simulator model/motion frequency sweep data—PB/δ_{lat}.
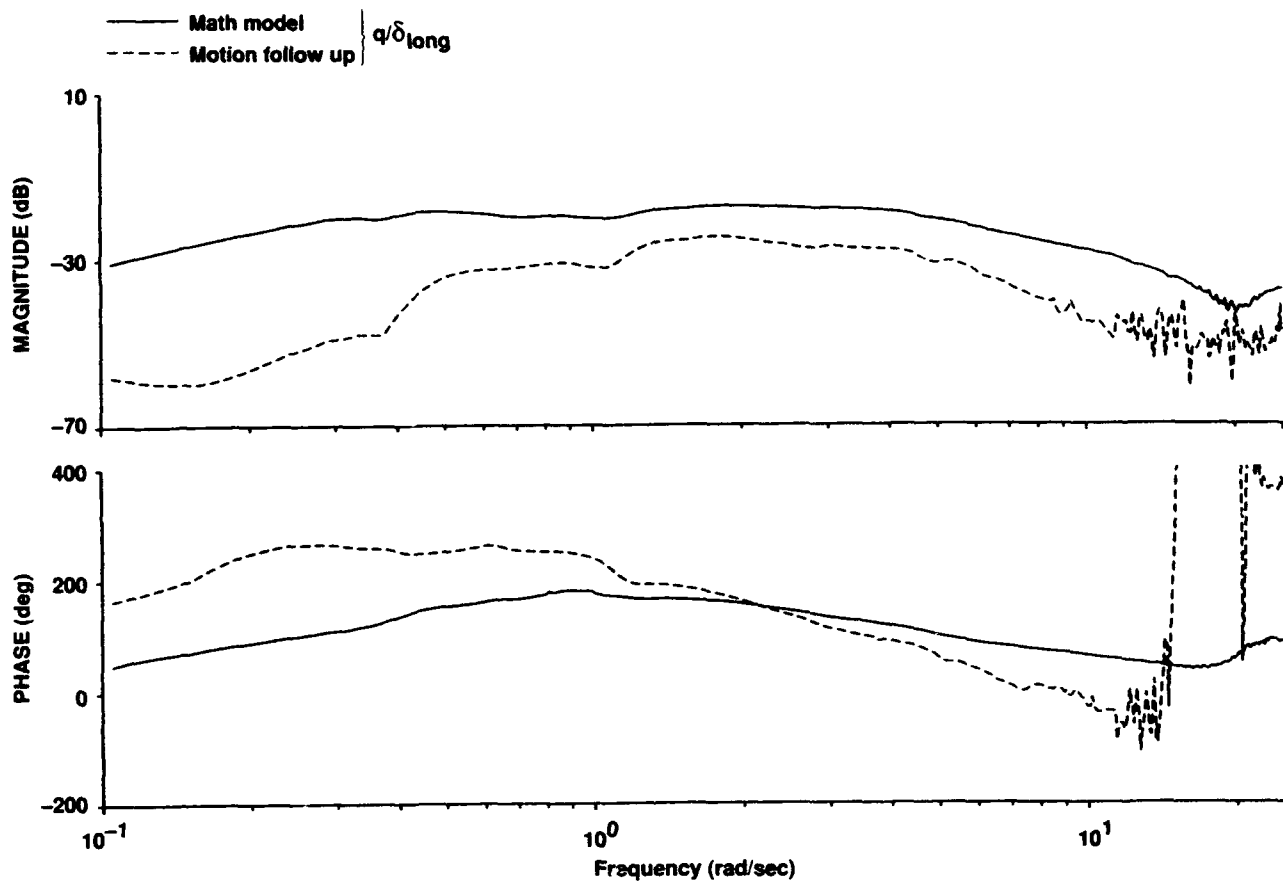
Figure 33. Simulator model/motion frequency sweep data—QB/δ_{long}.
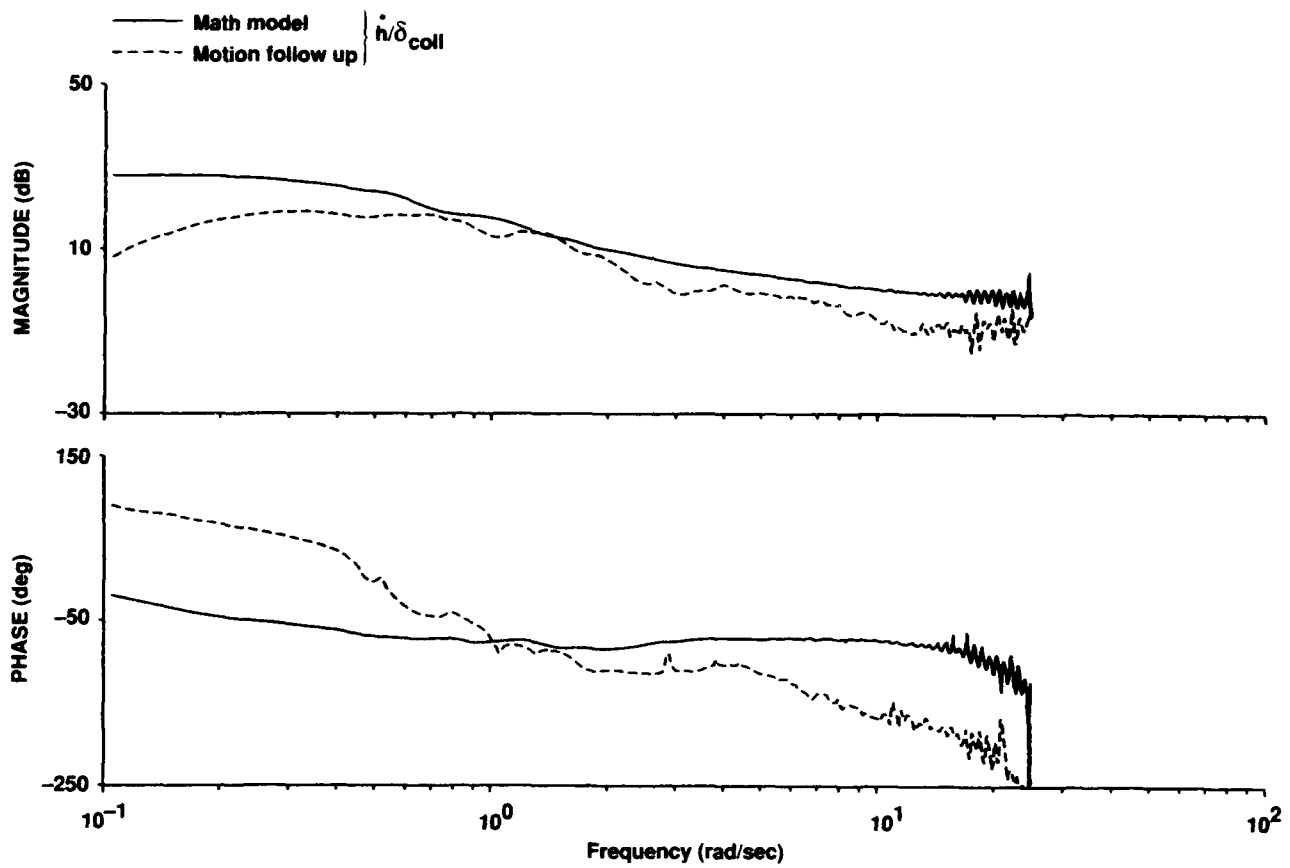
Figure 34. Simulator model/motion frequency sweep data—ALTD/δ_{coll}.
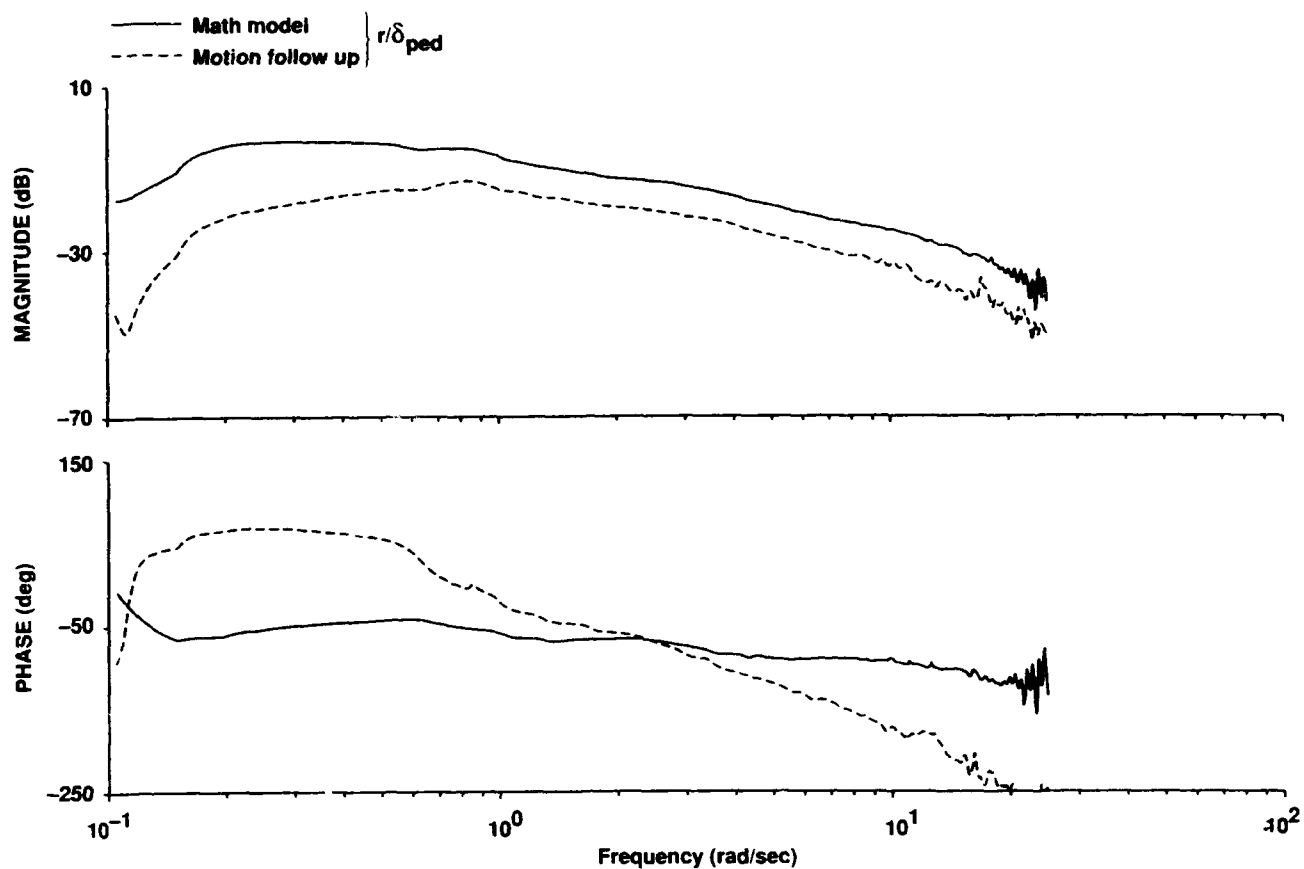
Figure 35. Simulator model/motion frequency sweep data—RB/δ_{ped}.

	Experience	
	Recent UH-60 helicopter (hours)	VMS simulator (hours)
Pilot 1	>250	~40
Pilot 2	~30	>150
Pilot 3	~100	new
Pilot 4	~25	>250
Pilot 5	>100	~20

Figure 36. Pilot experience.
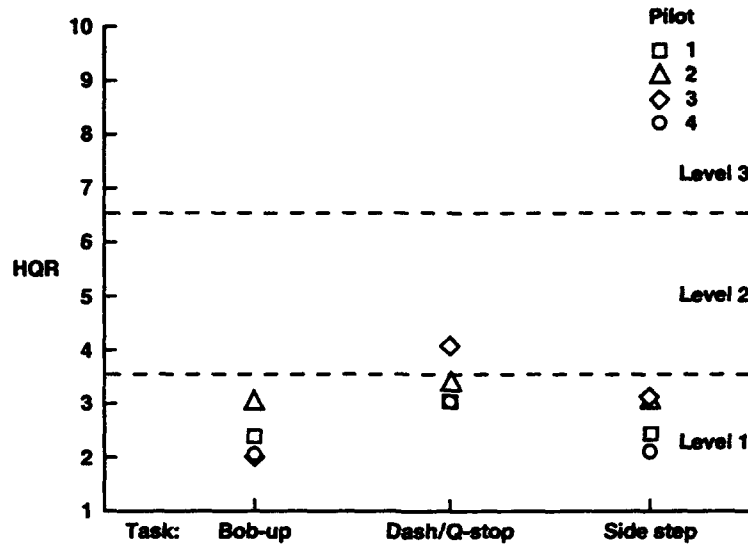
Note: Pilot ratings have been averaged when more than one rating has been given for a task.

Figure 37. Handling qualities rating data—flight test.
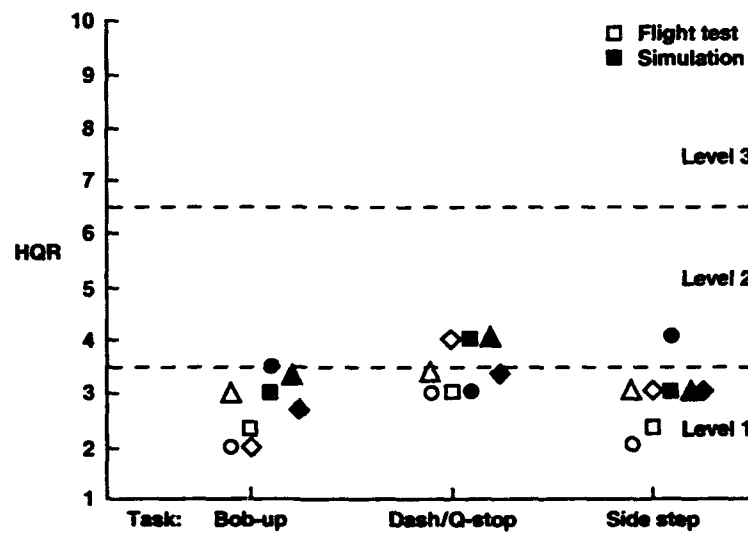
Note: HQR values have been averaged when more than one evaluation was made.

Figure 38. Handling qualities rating data—1989 versus flight test.

79

Note: Pilot ratings have been averaged when more than one rating has been given for a task.
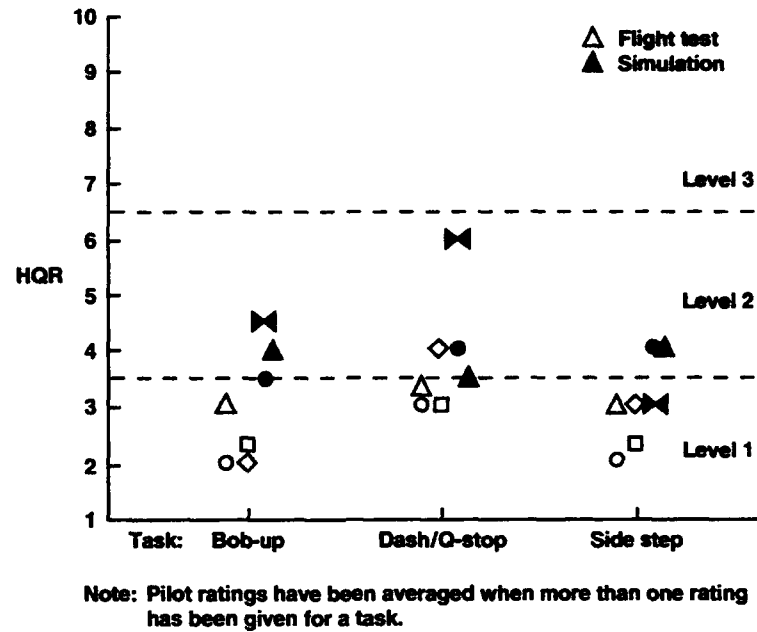
Figure 39. Handling qualities rating data—1990 versus flight test.

Note: HQR values have been averaged when more than one evaluation was made.
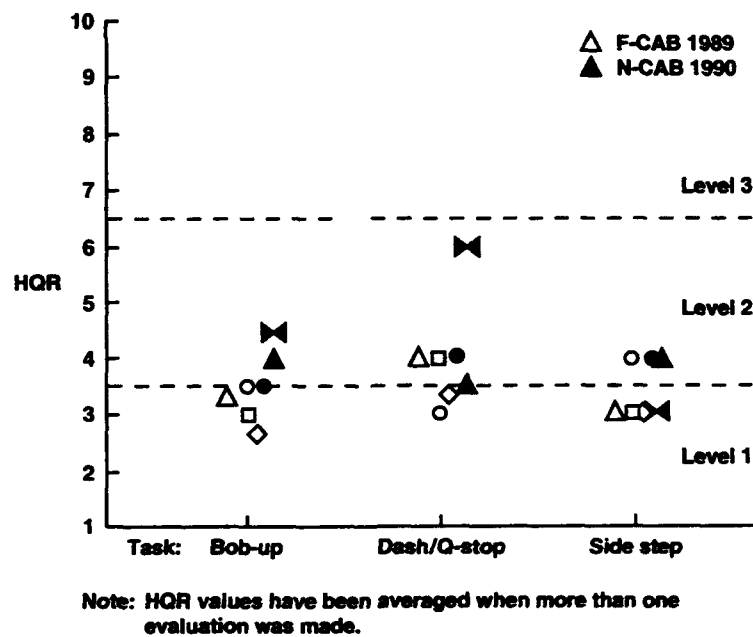
Figure 40. Handling qualities rating data—1989 simulation versus 1990 simulation.
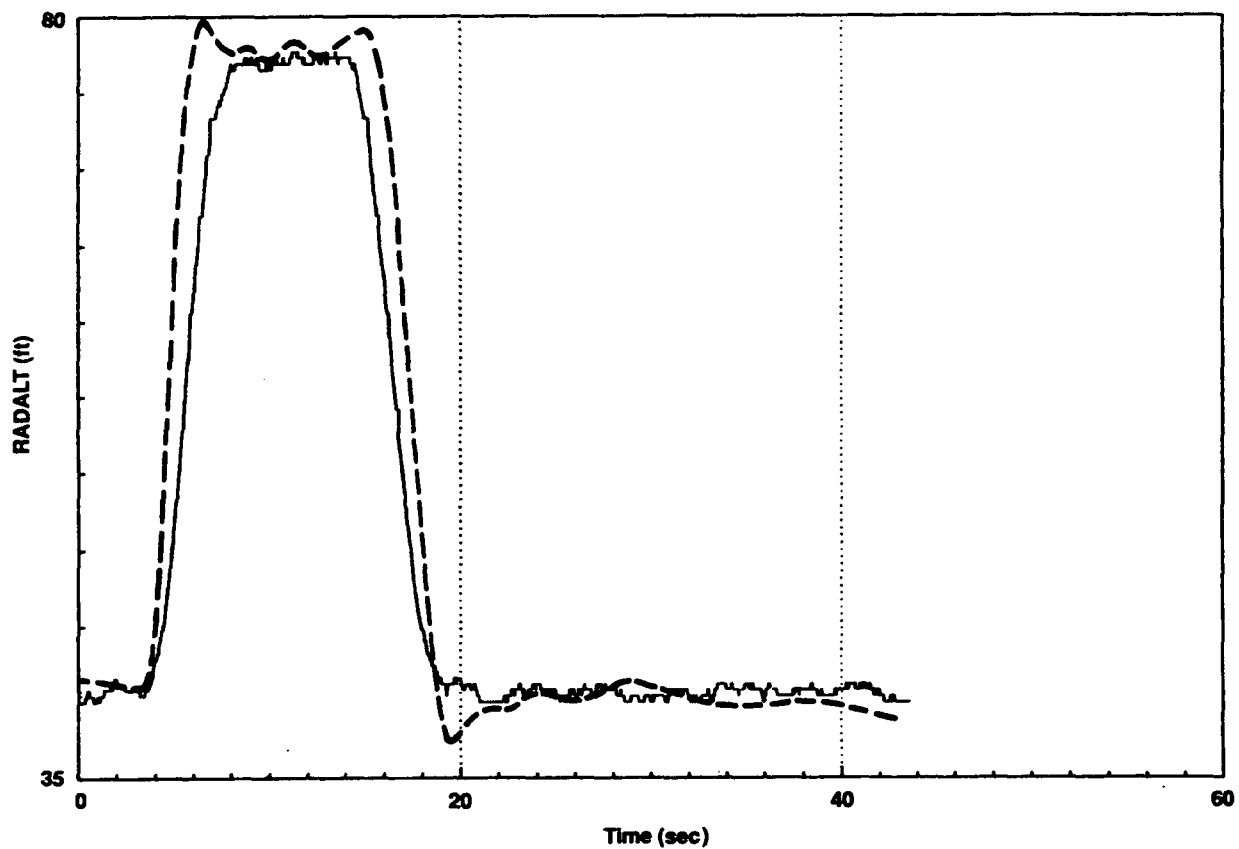
Figure 41. Pilot 2, bob-up task. (a) Flight versus simulator.
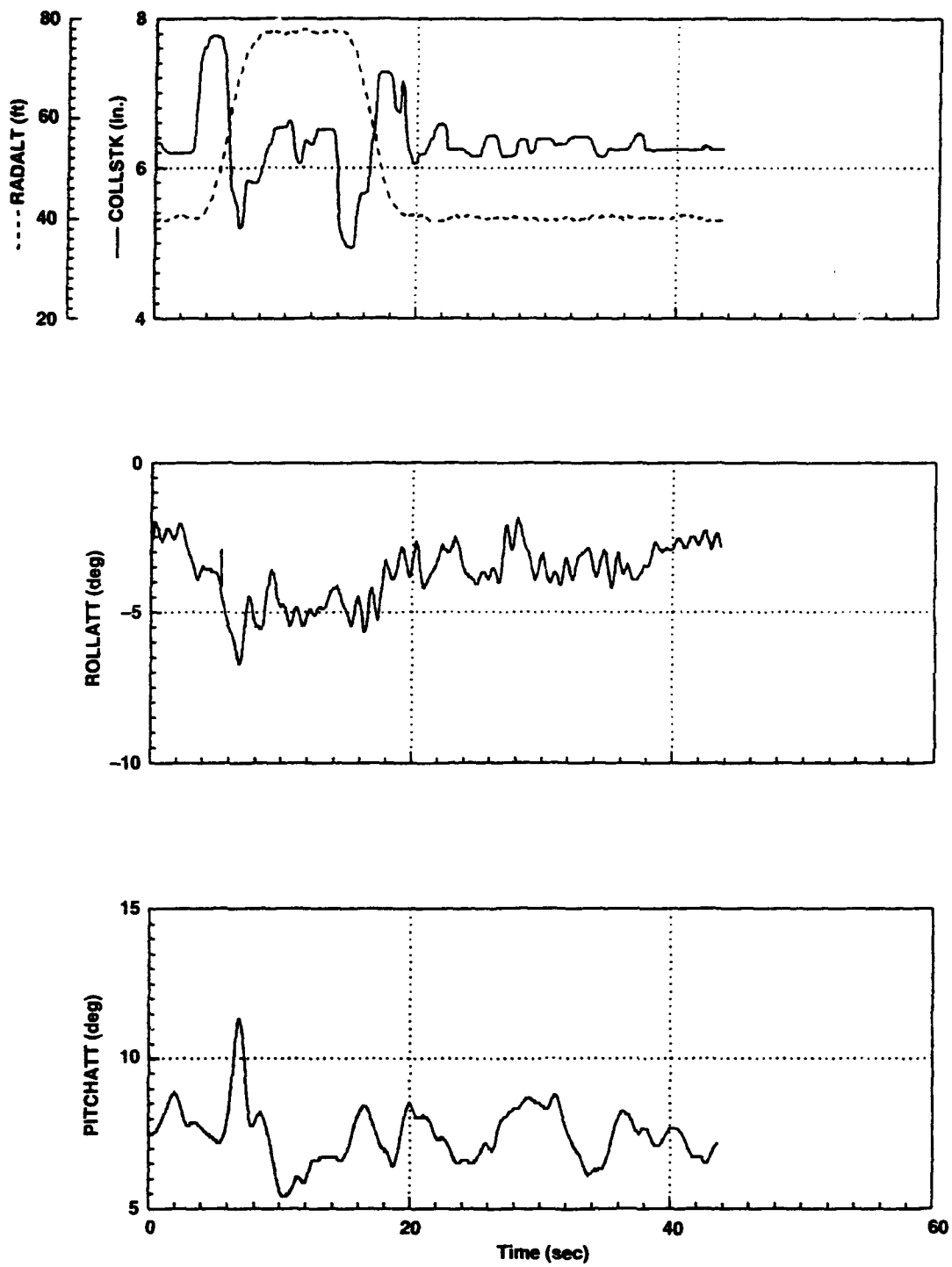
Figure 41. Pilot 2, bob-up task (Continued). (b) Flight data.
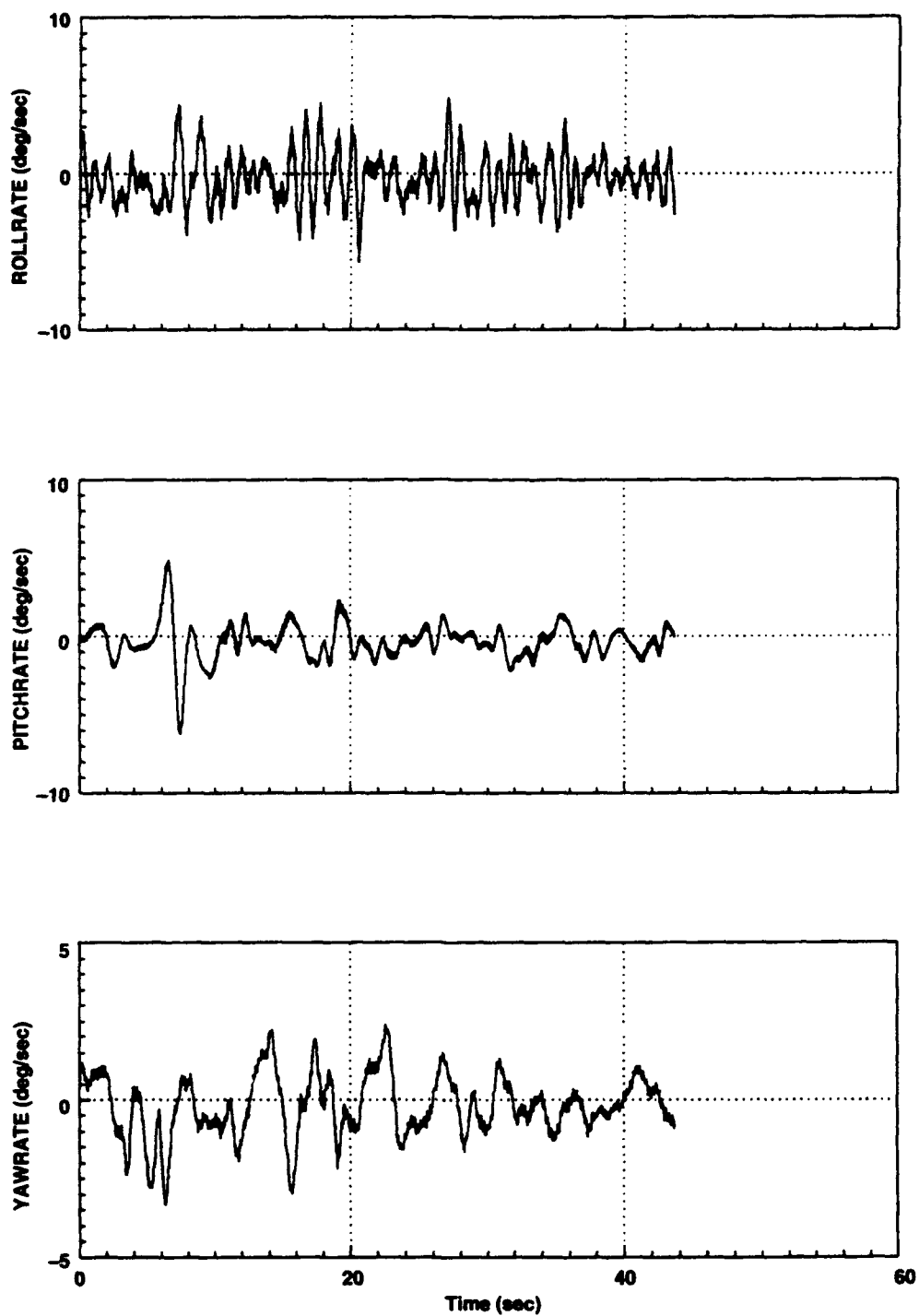
Figure 41. Pilot 2, bob-up task (Continued). (c) Flight data.
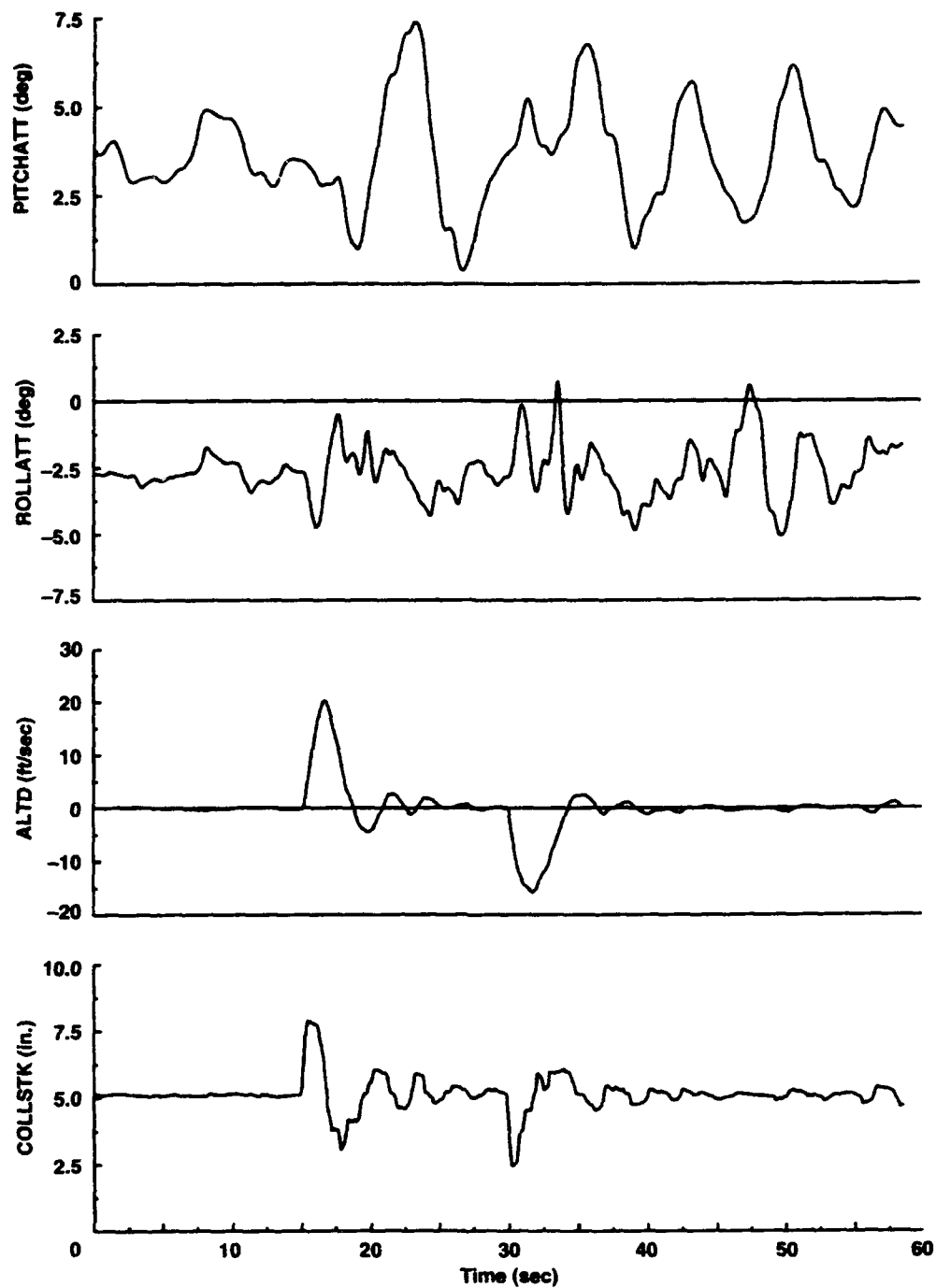
Figure 41. Pilot 2, bob-up task (Continued). (d) Simulator data.
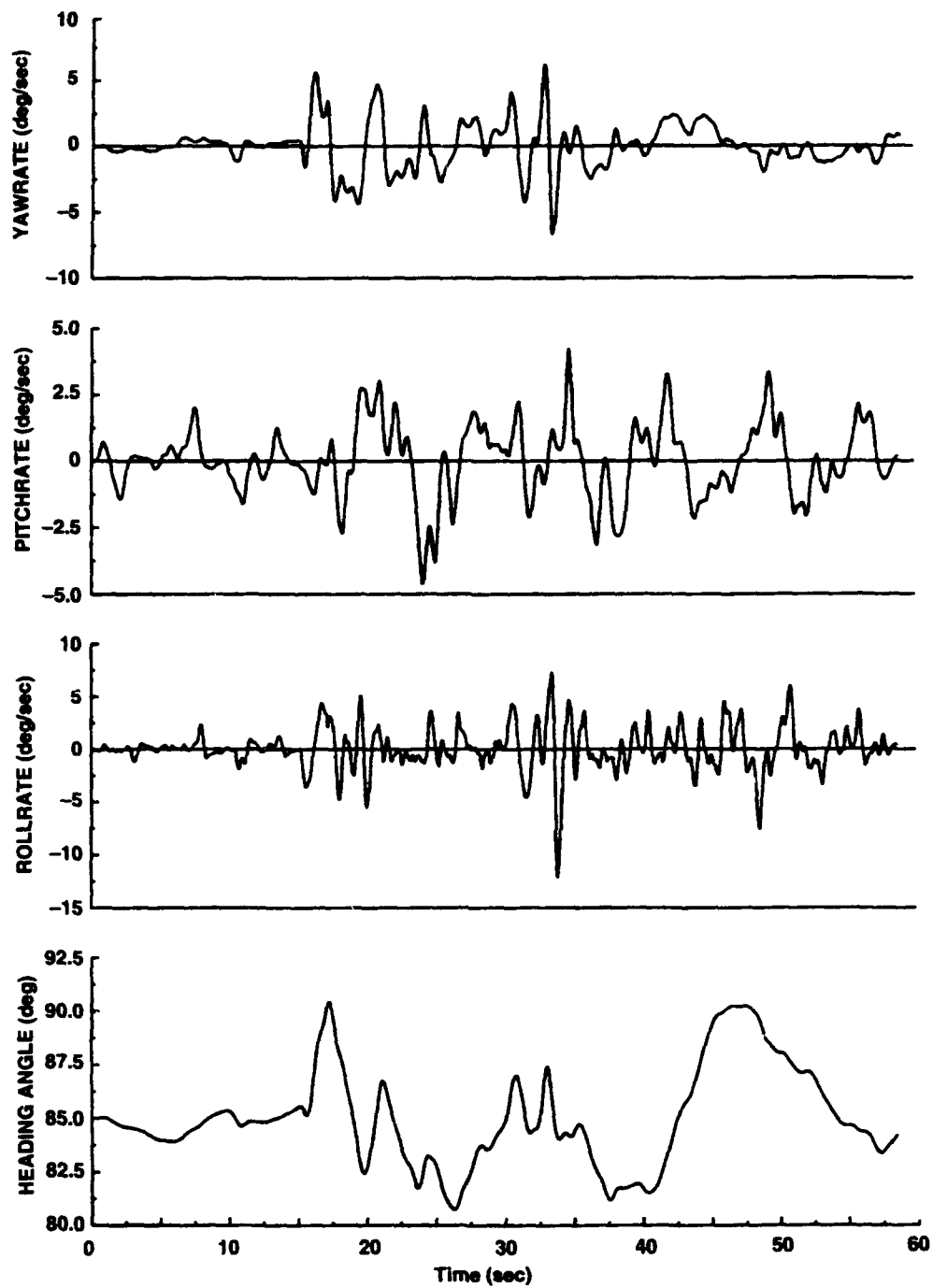
Figure 41. Pilot 2, bob-up task (Concluded). (e) Simulator data.

85
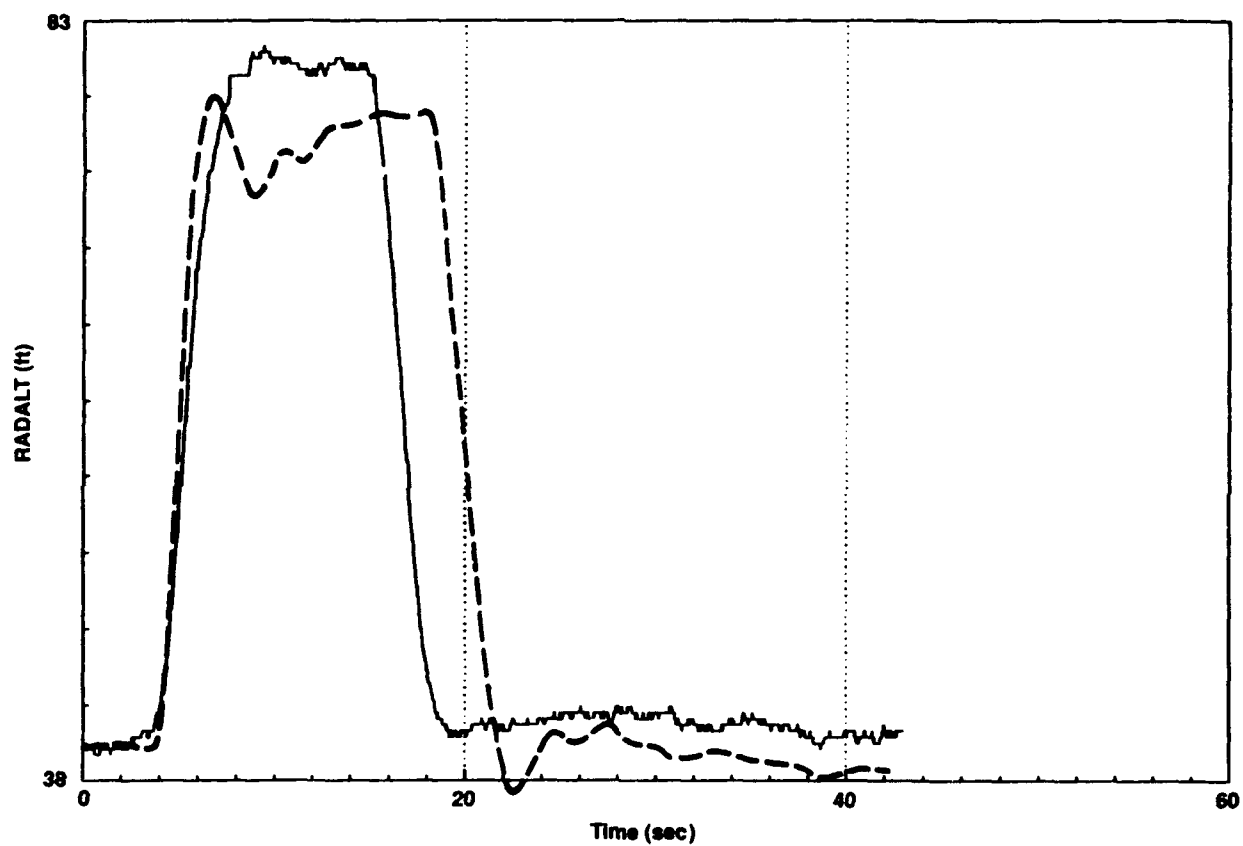
Figure 42. Pilot 4, bob-up task. (a) Flight versus simulator.
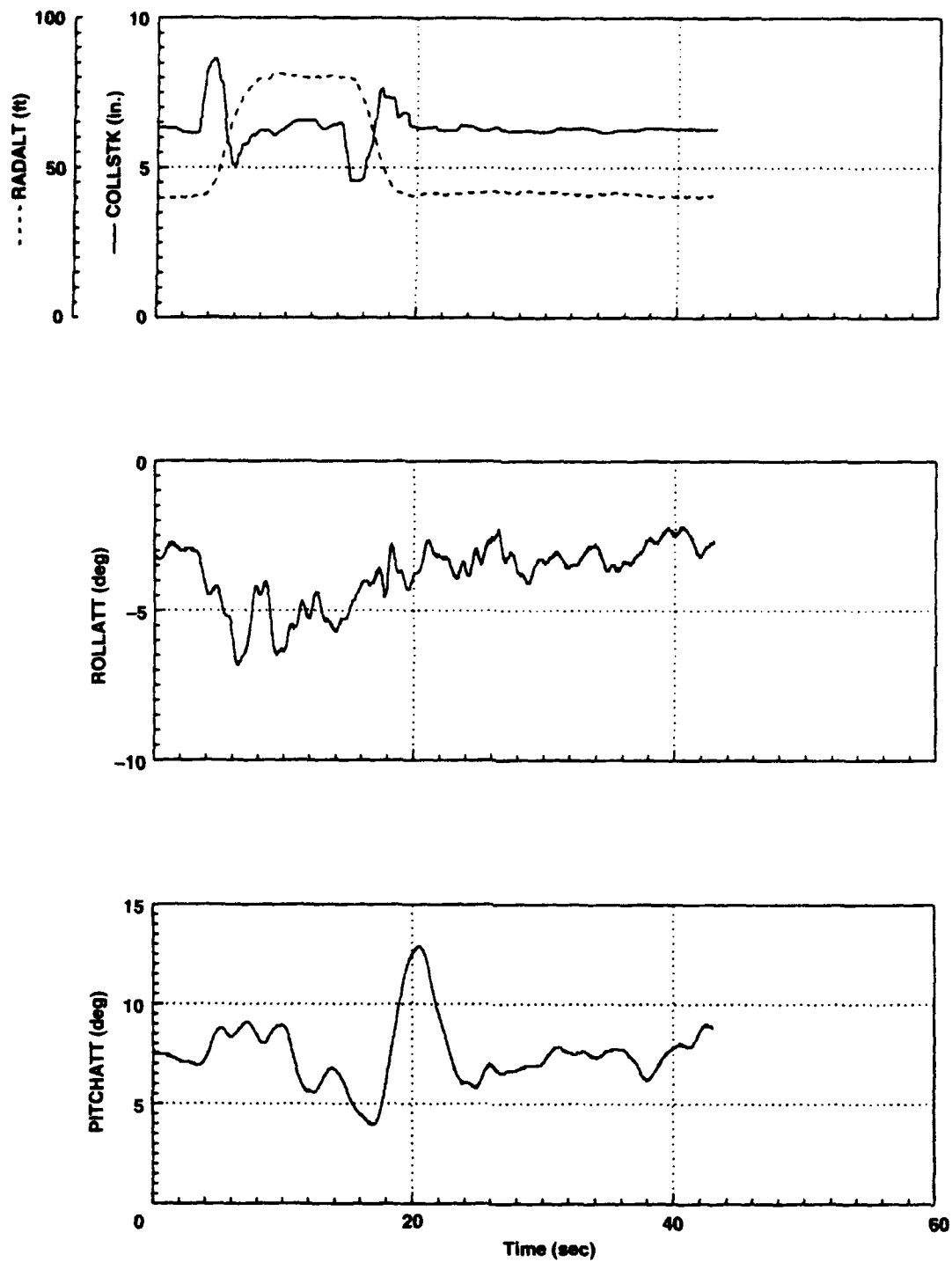
Figure 42. Pilot 4, bob-up task (Continued). (b) Flight data.
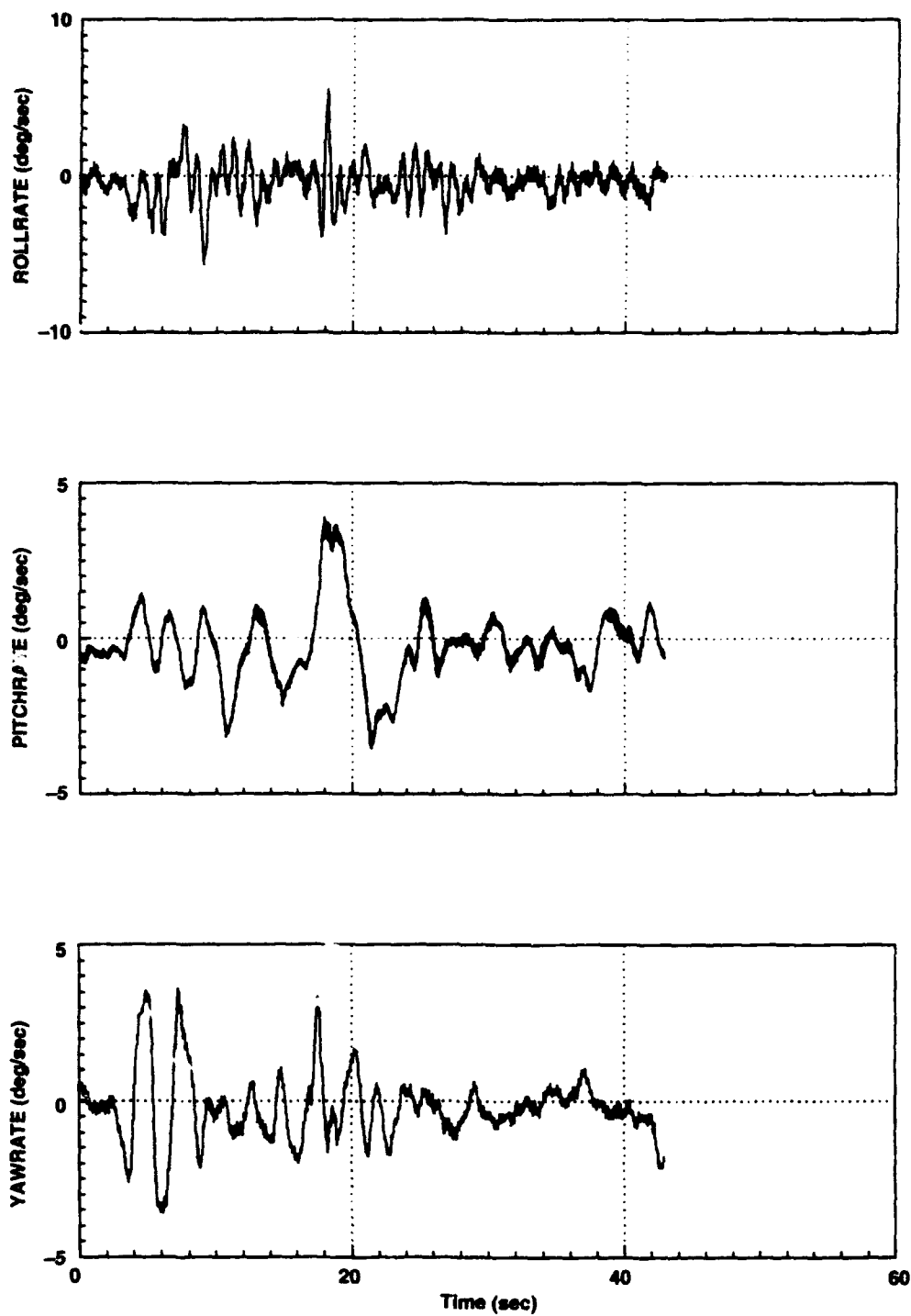
Figure 42. Pilot 4, bob-up task (Continued). (c) Flight data.
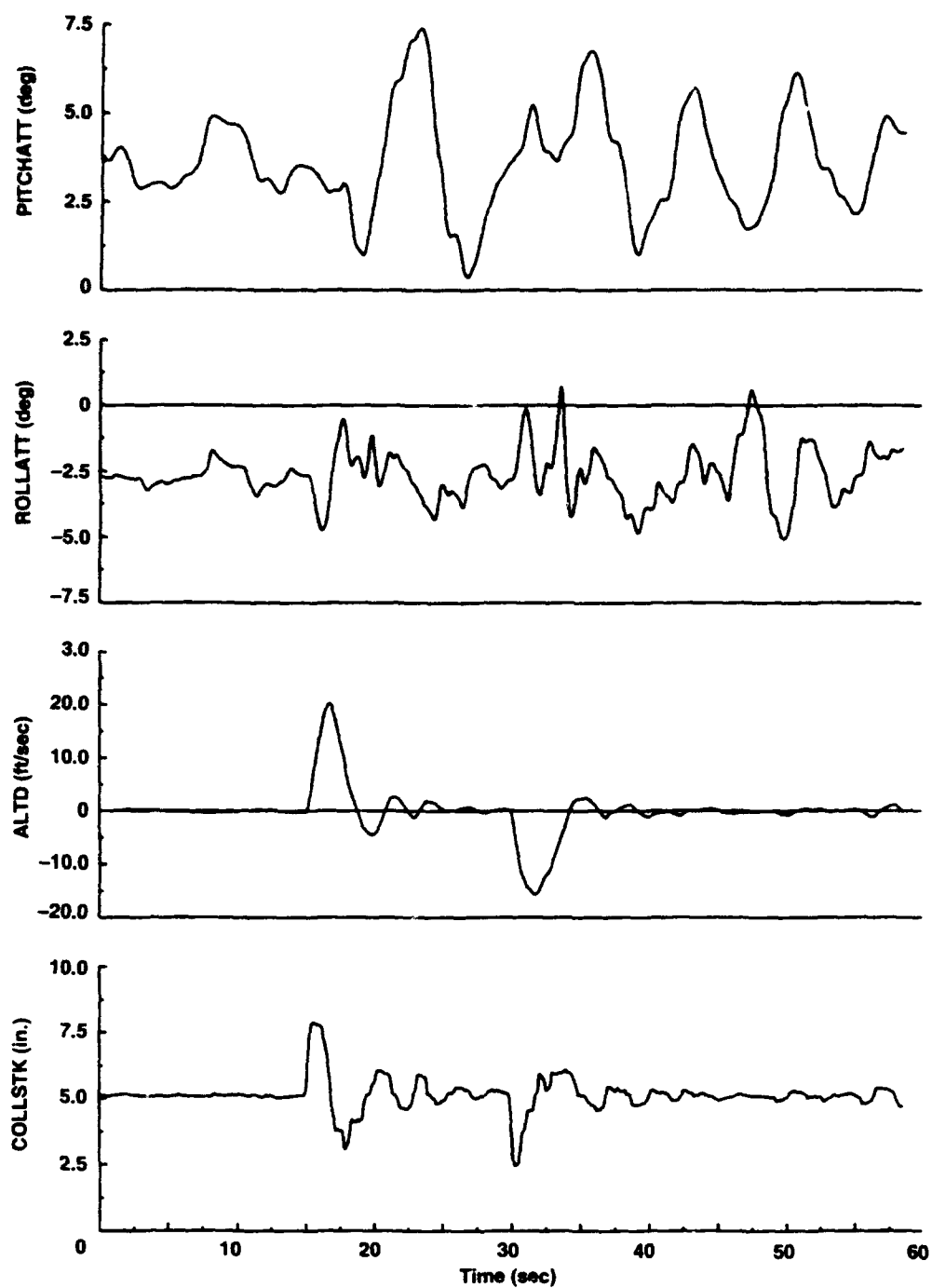
Figure 42. Pilot 4, bob-up task (Continued). (d) Simulator data.
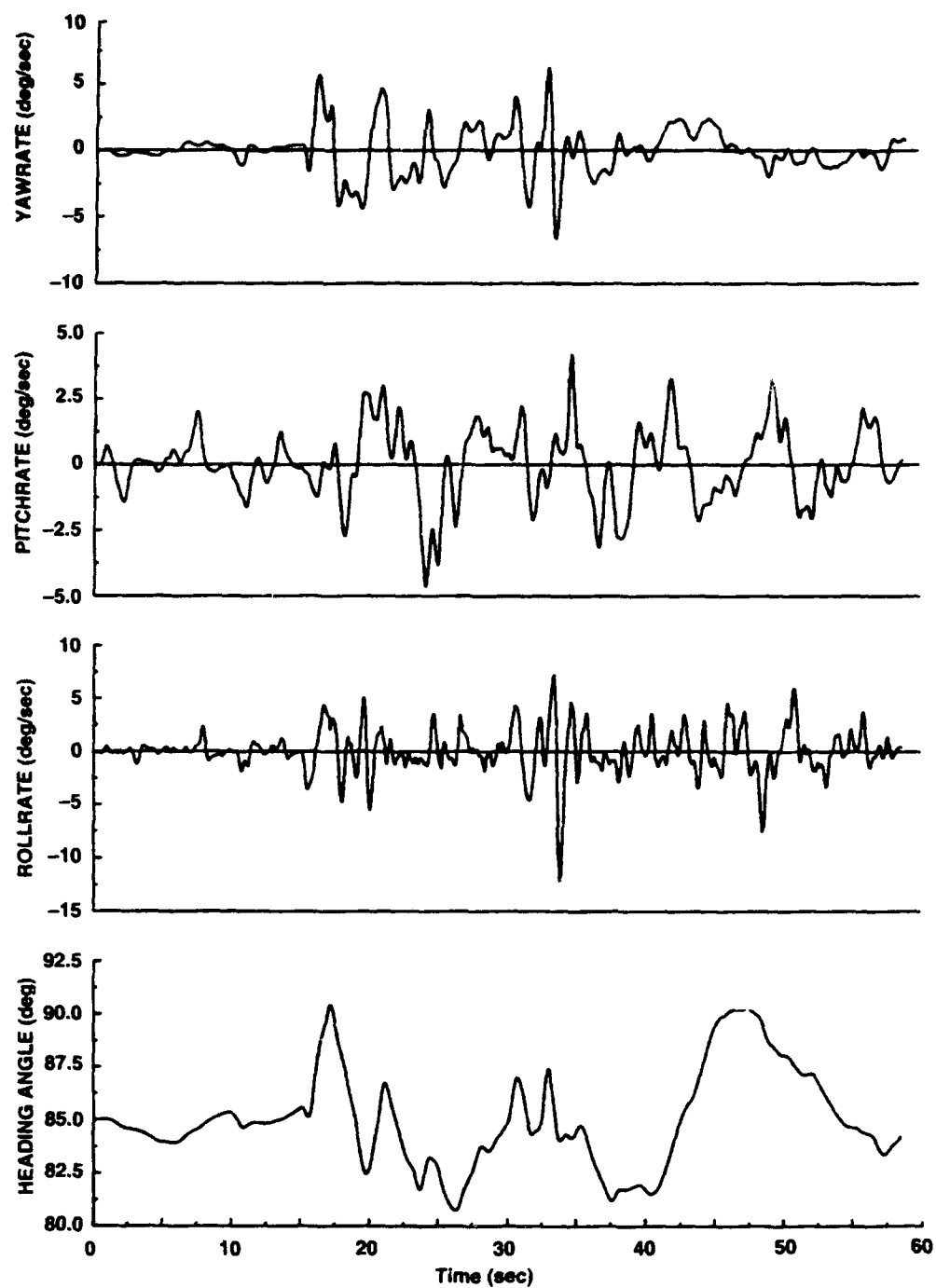
Figure 42. Pilot 4, bob-up task (Concluded). (e) Simulator data.

Pilot 2

Variable	Flight				Simulation			
	min	max	avg	σ	min	max	avg	σ
Roll attitude	-6.73	-1.85	-3.71	0.98	-4.55	0.22	-2.67	0.73
Roll rate	-5.64	4.82	-0.33	1.58	-4.50	4.76	0.006	1.28
Pitch attitude	5.39	11.33	7.45	0.93	2.36	4.86	3.65	0.61
Pitch rate	-6.21	4.85	-0.35	1.17	-2.92	2.11	0.02	0.58
Yaw attitude	—	—	—	—	75.08	86.31	81.70	2.46
Yaw rate	-3.34	2.39	-0.20	0.98	-4.63	4.20	-0.011	1.36

Pilot 4

Variable	Flight				Simulation			
	min	max	avg	σ	min	max	avg	σ
Roll attitude	-6.82	-2.21	-3.79	1.06	-5.08	0.74	-2.65	0.98
Roll rate	-5.64	5.53	-0.41	1.22	-12.03	7.37	0.02	2.07
Pitch attitude	3.91	12.91	7.49	1.63	0.37	7.40	3.63	1.45
Pitch rate	-3.53	3.89	-0.26	1.18	-4.66	4.23	0.005	1.35
Yaw attitude	—	—	—	—	80.73	90.44	85.01	2.26
Yaw rate	-3.59	3.60	-0.22	1.11	-6.69	6.23	0.01	1.71

Attitudes are in degrees, rates are in degrees/sec.

Figure 43. Summary of data for bob-up task.
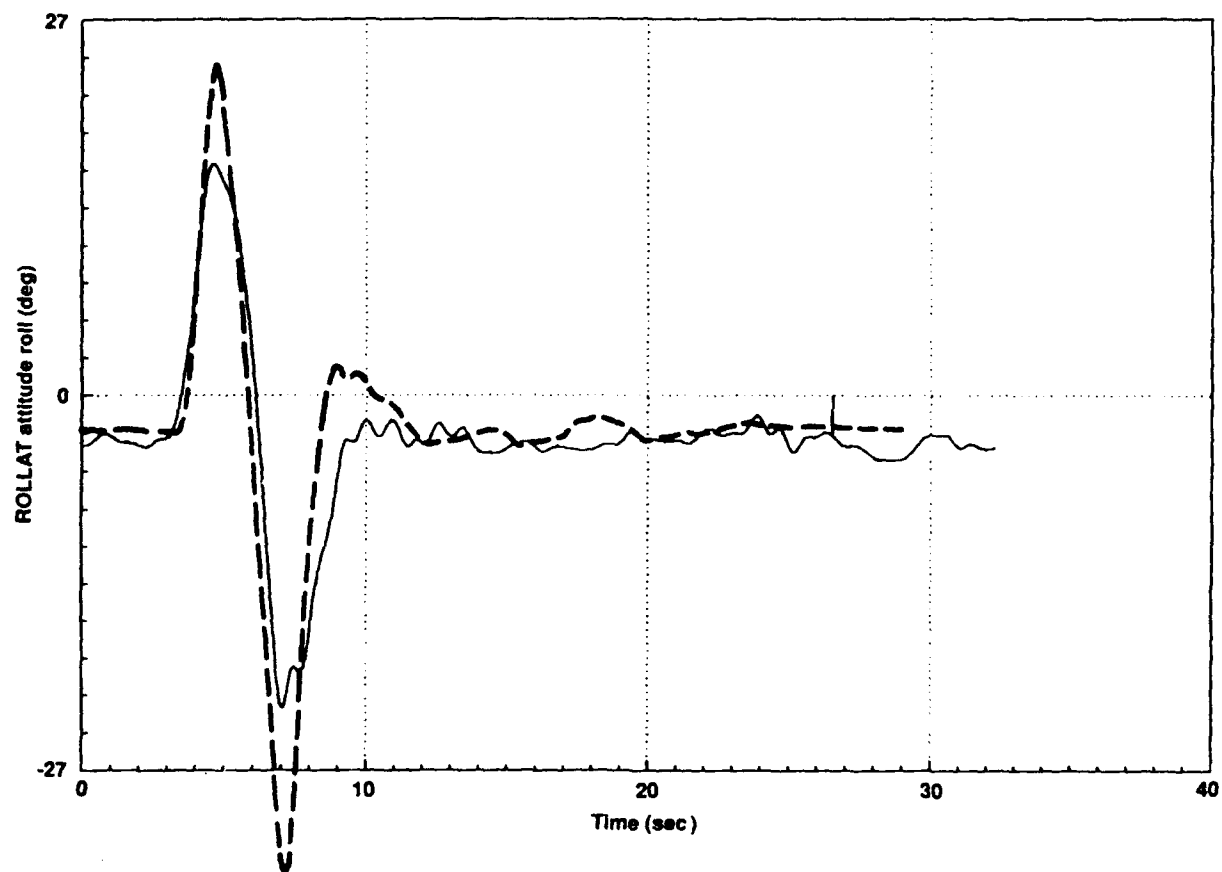
Figure 44. Pilot 2, side-step task. (a) Flight versus simulator (left-to-right side step).
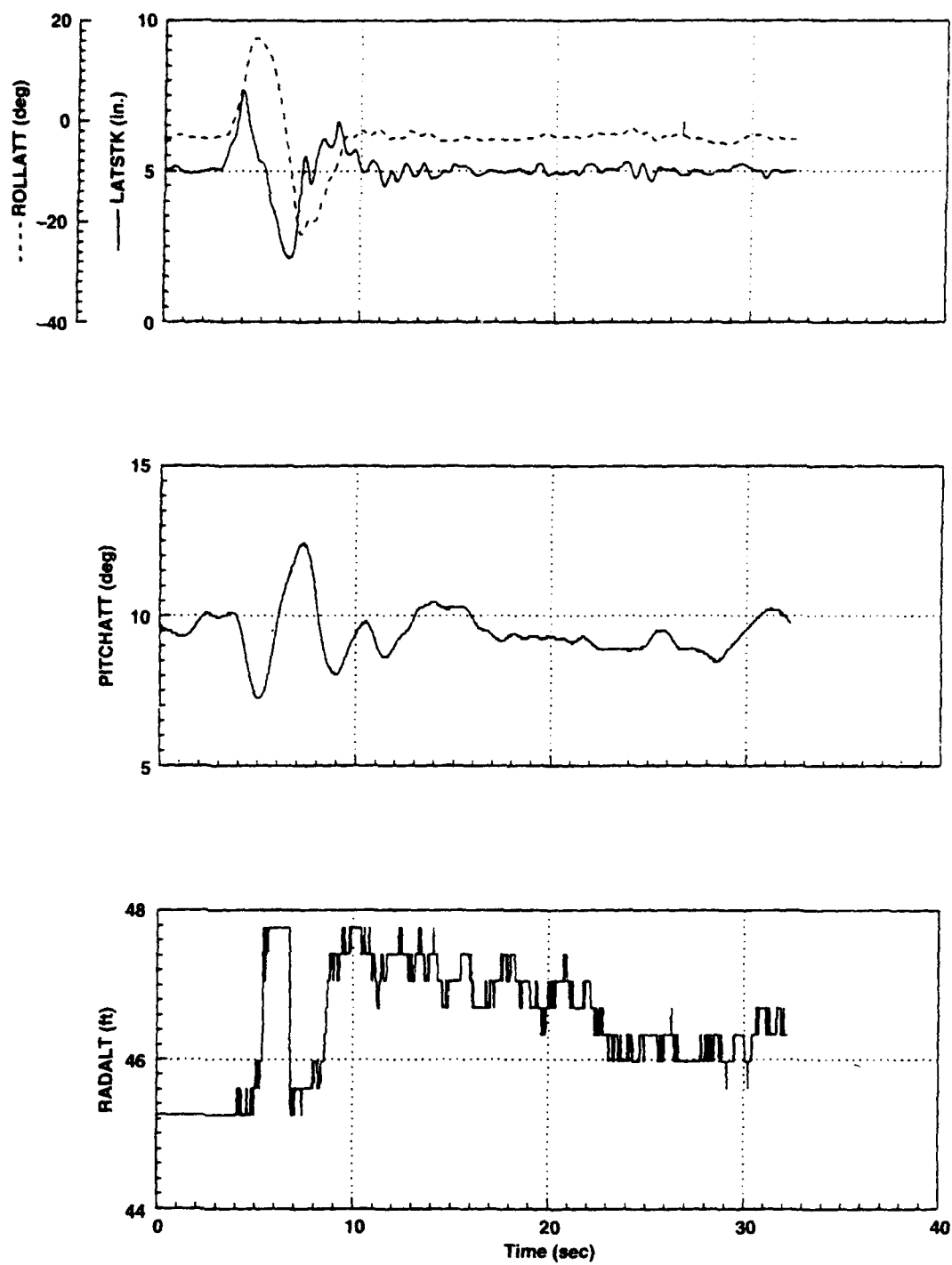
Figure 44. Pilot 2, side-step task (Continued). (b) Flight (left to right).
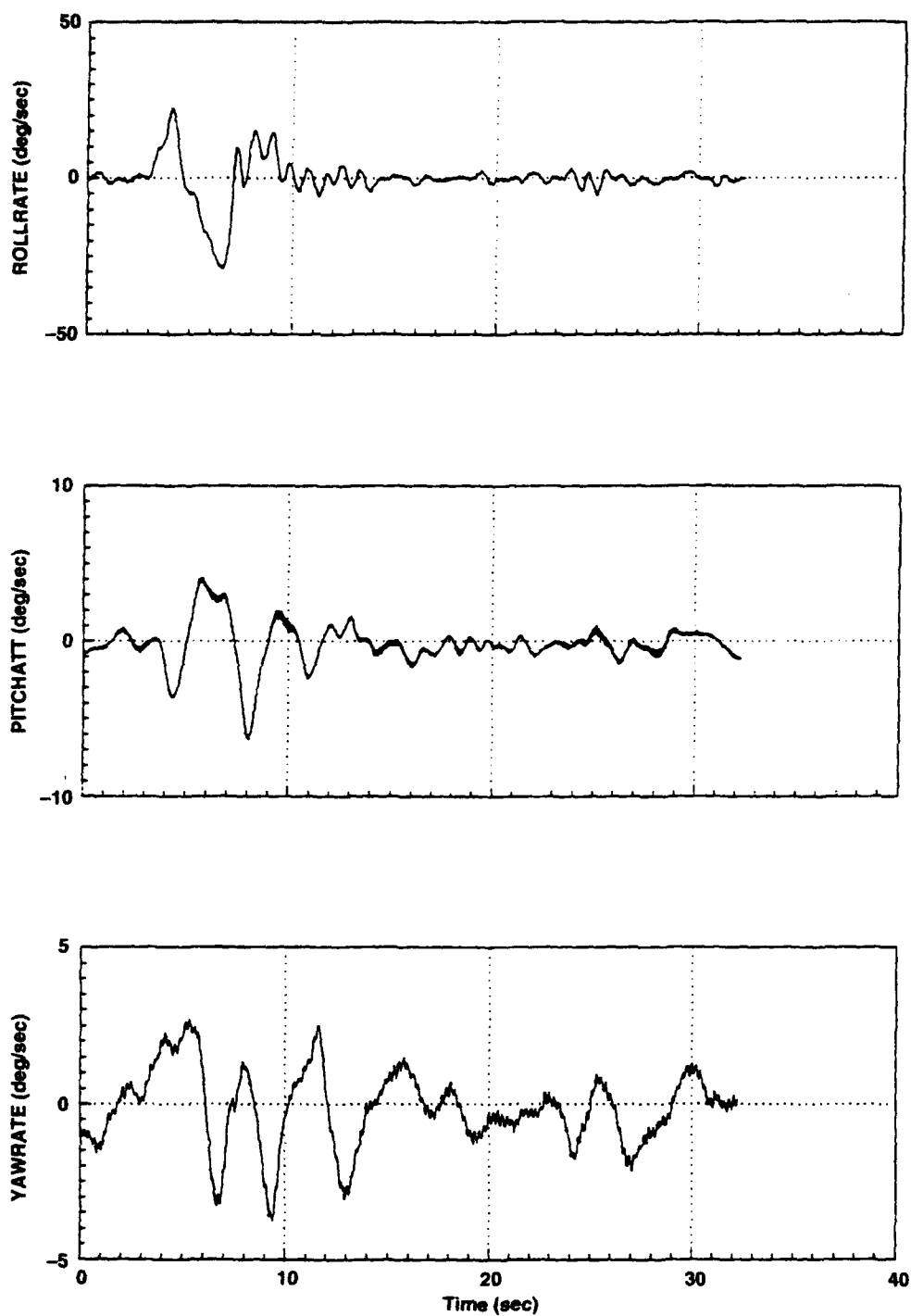
Figure 44. Pilot 2, side-step task (Continued). (c) Flight (left to right).
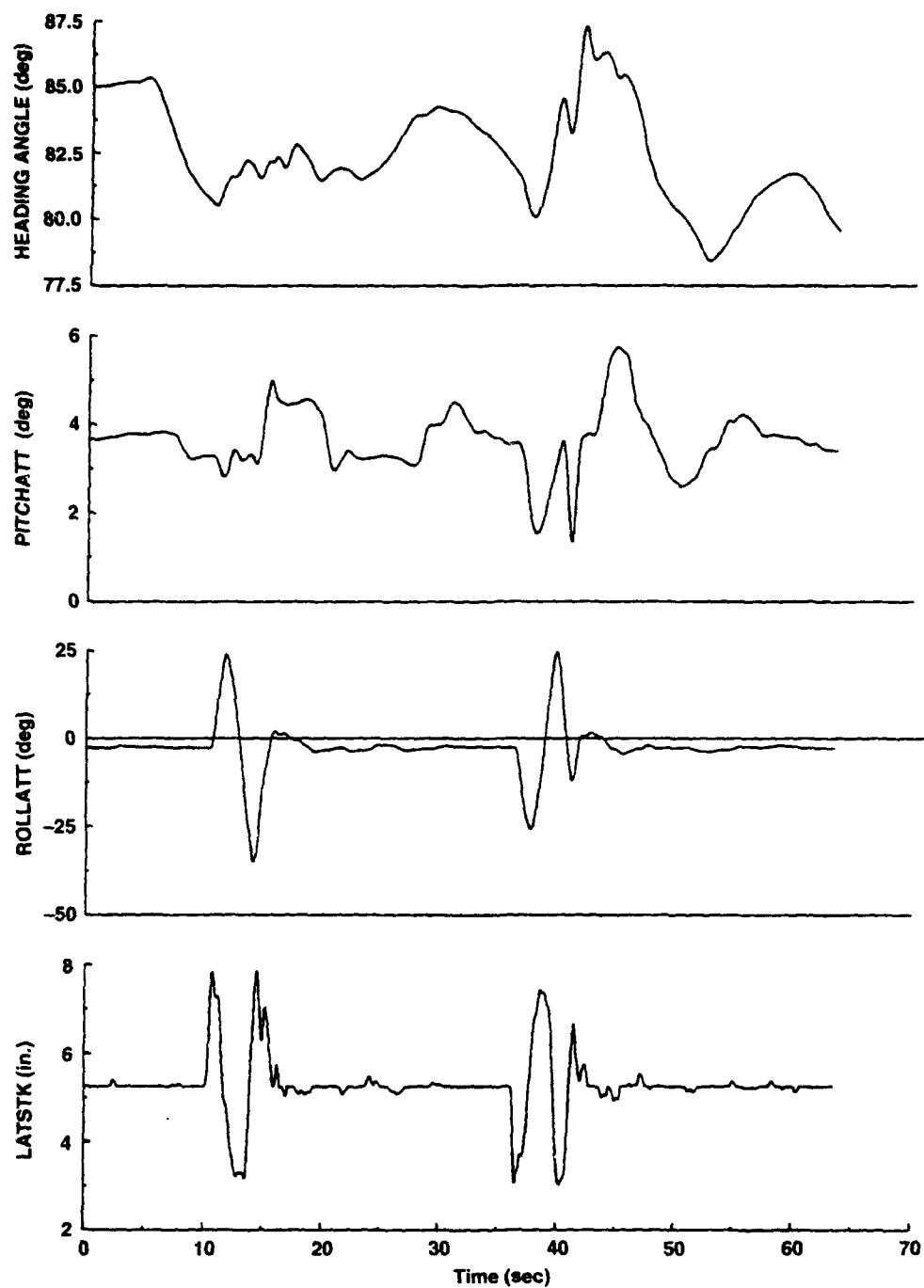
Figure 44. Pilot 2, side-step task (Continued). (d) Simulator (left to right).
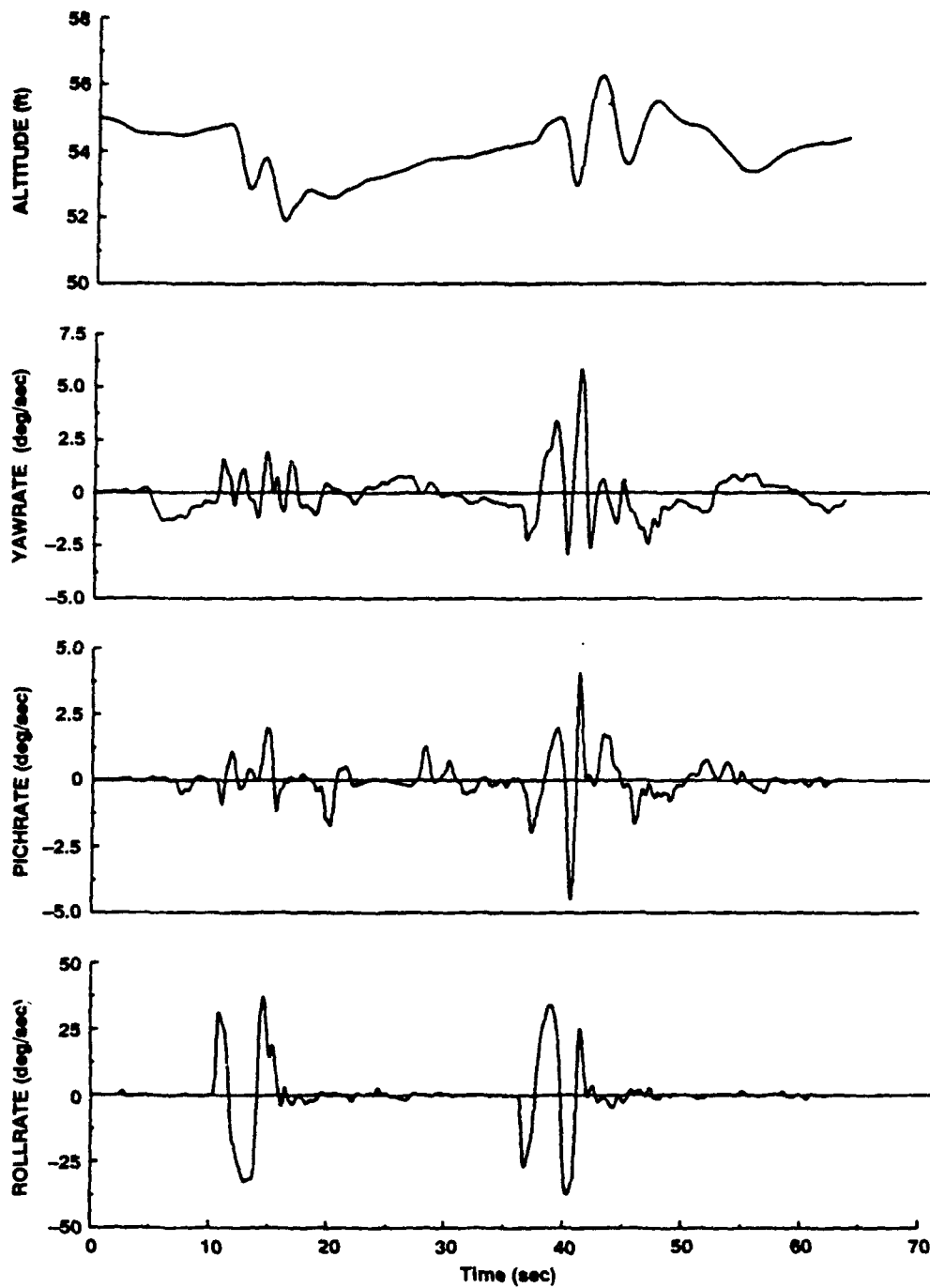
Figure 44. Pilot 2, side-step task (Continued). (e) Simulator (left to right).
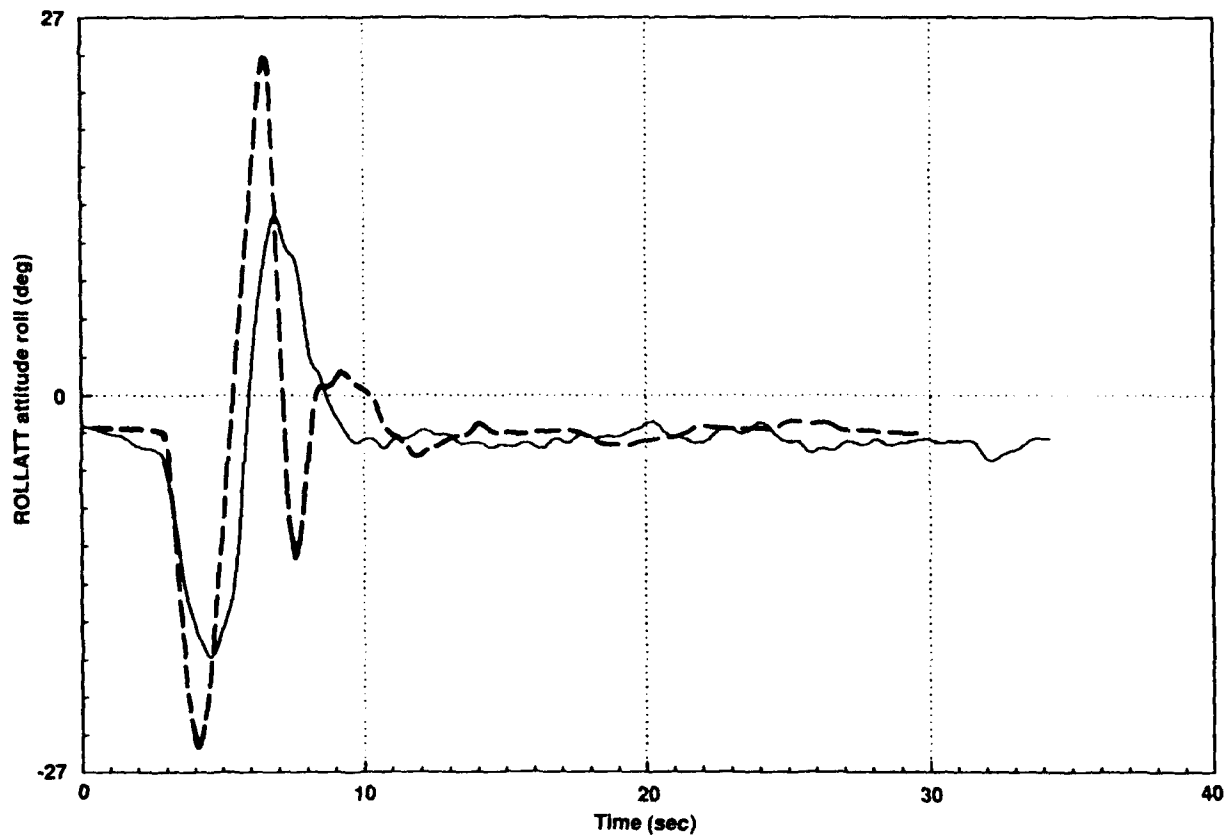
Figure 44. Pilot 2, side-step task. (f) Flight versus simulator (right-to-left side step) (Concluded).
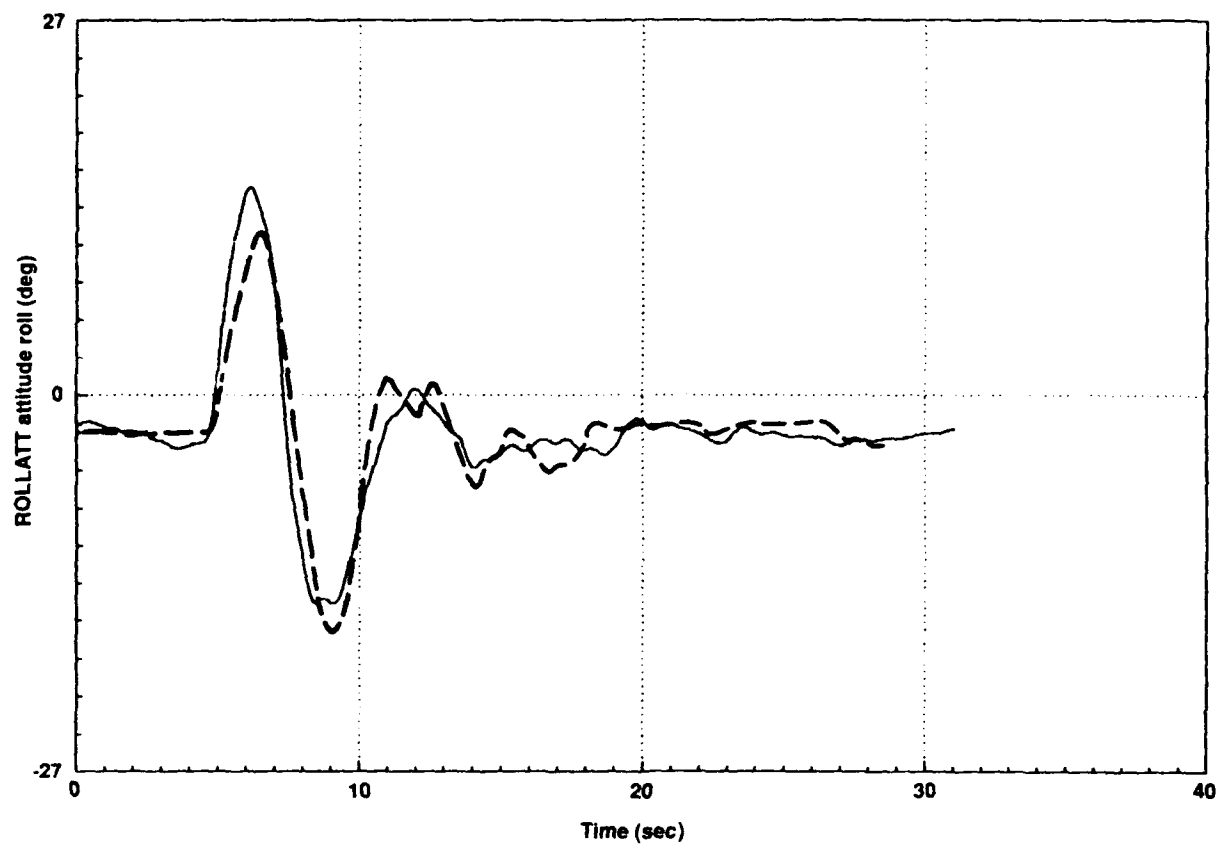
Figure 45. Pilot 4, side-step task. (a) Flight versus simulator (left-to-right side step).
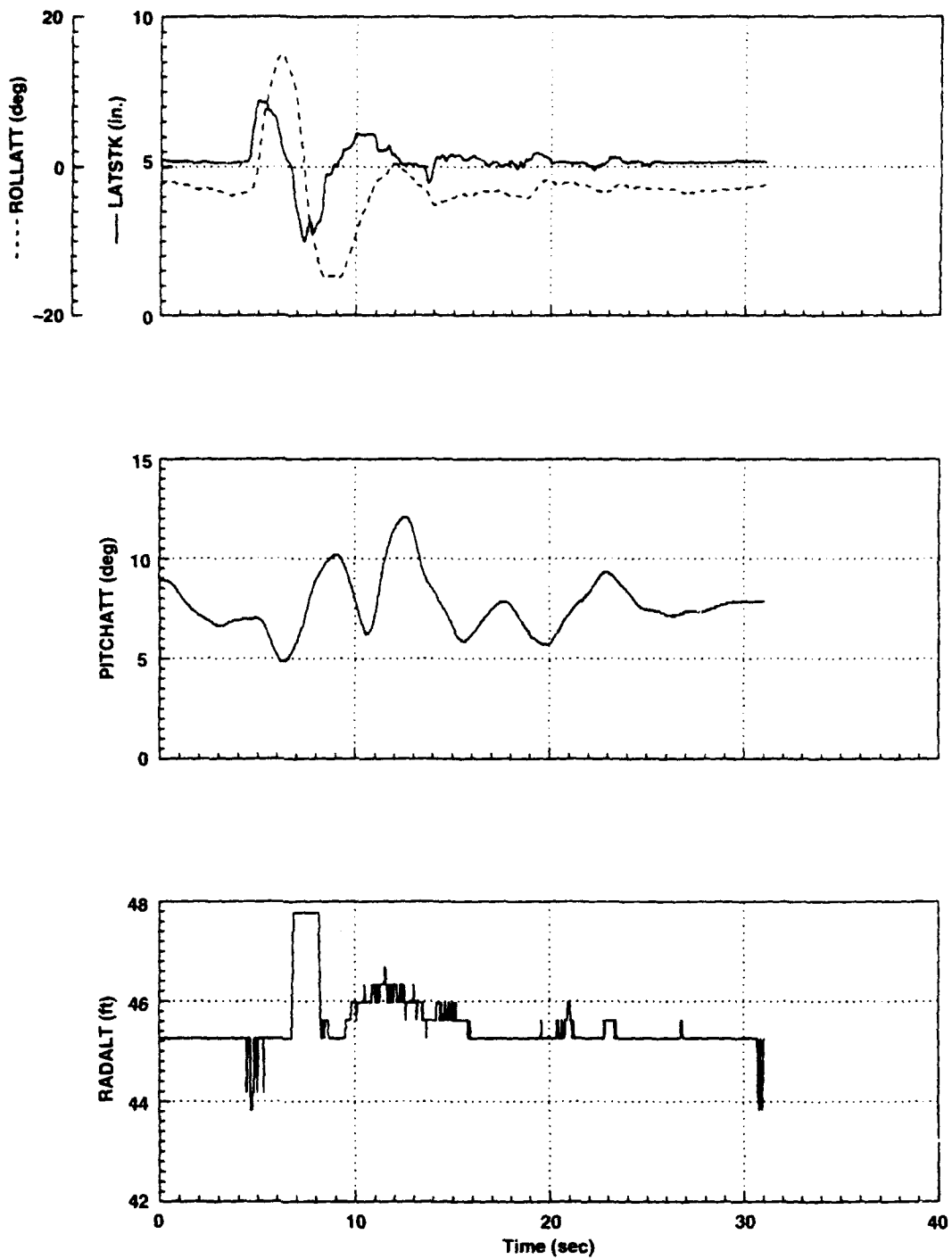
Figure 45. Pilot 4, side-step task (Continued). (b) Flight (left to right).
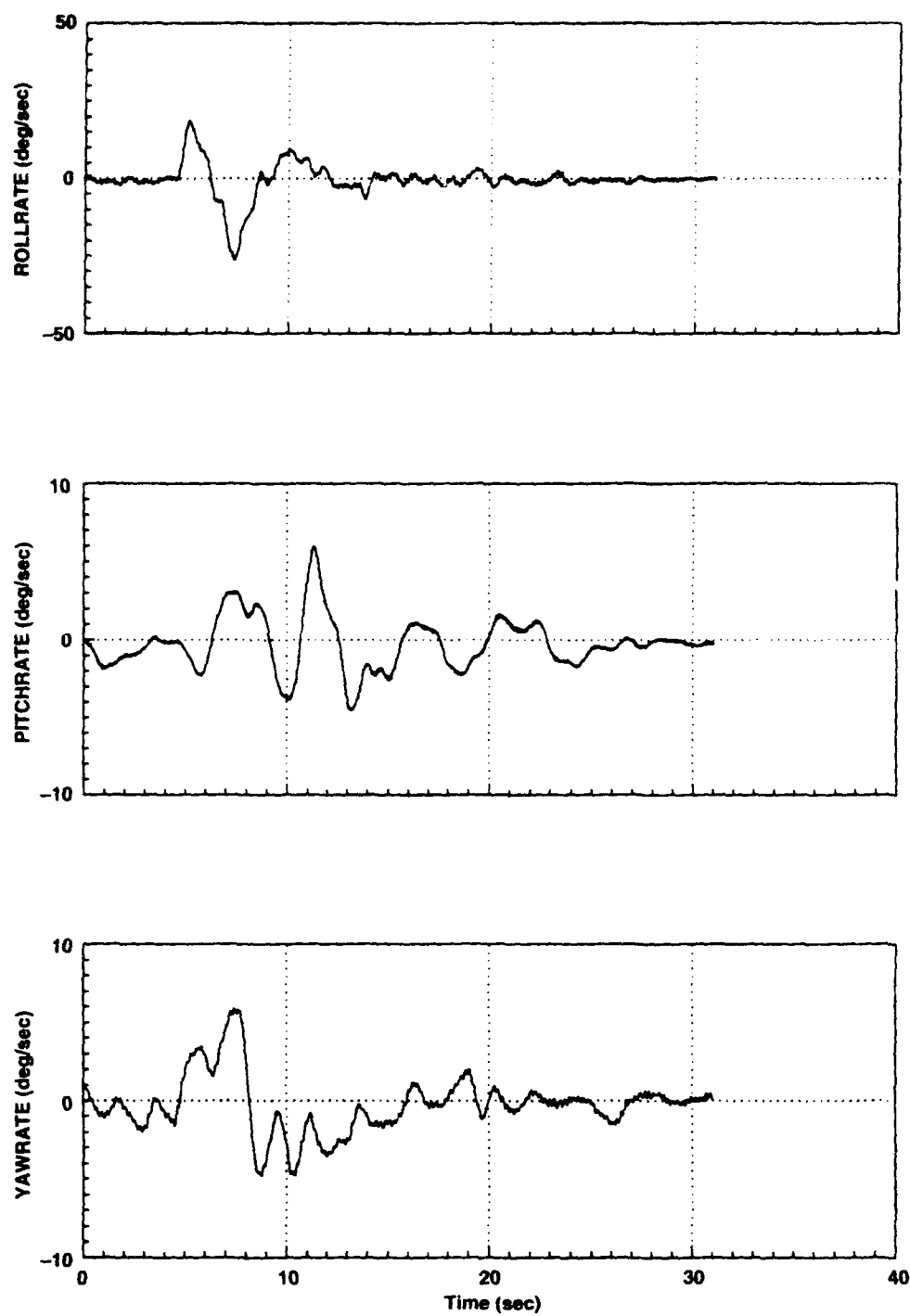
Figure 45. Pilot 4, side-step task (Continued). (c) Flight (left to right).
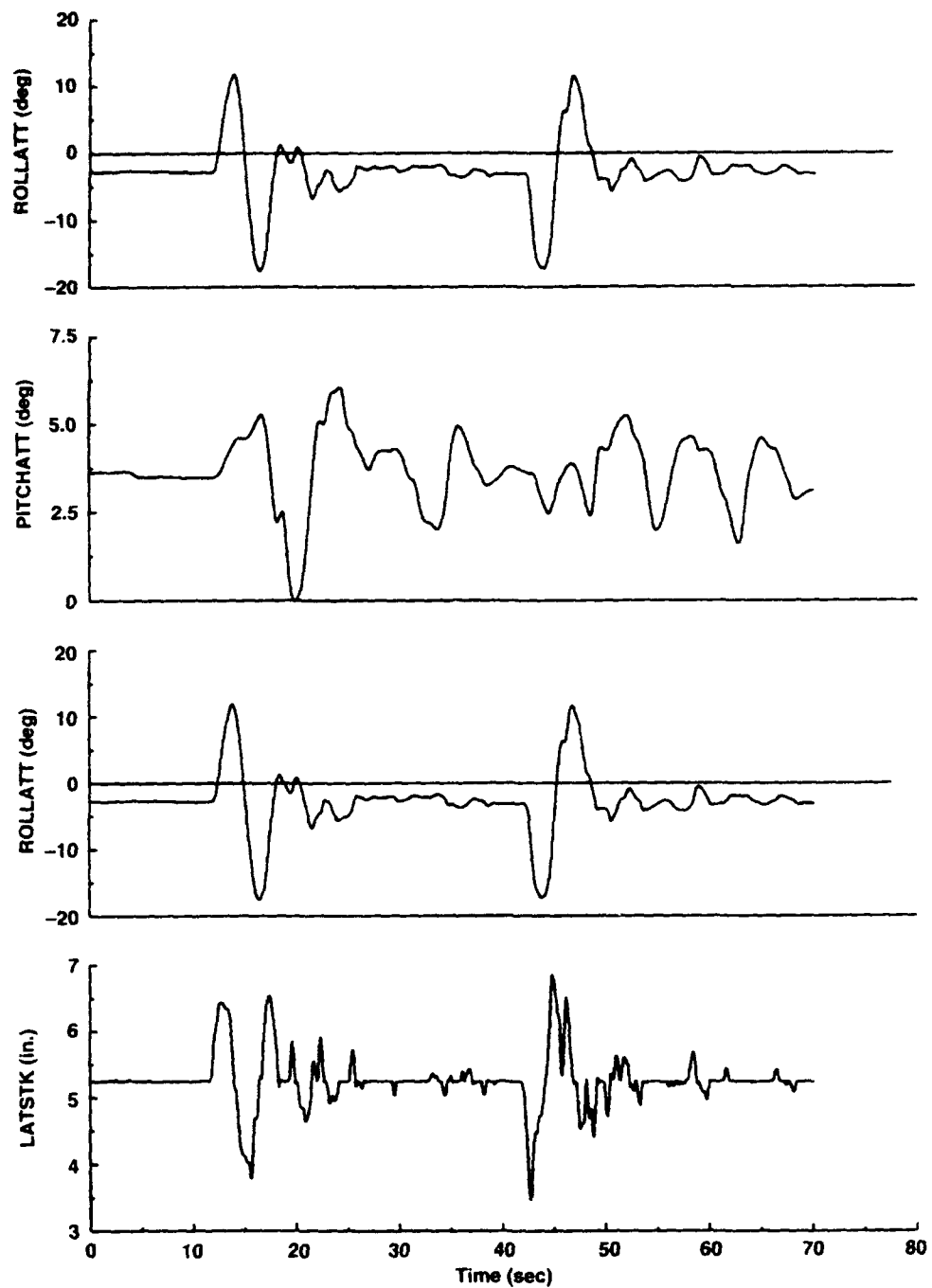
Figure 45. Pilot 4, side-step task (Continued). (d) Simulator (left to right).
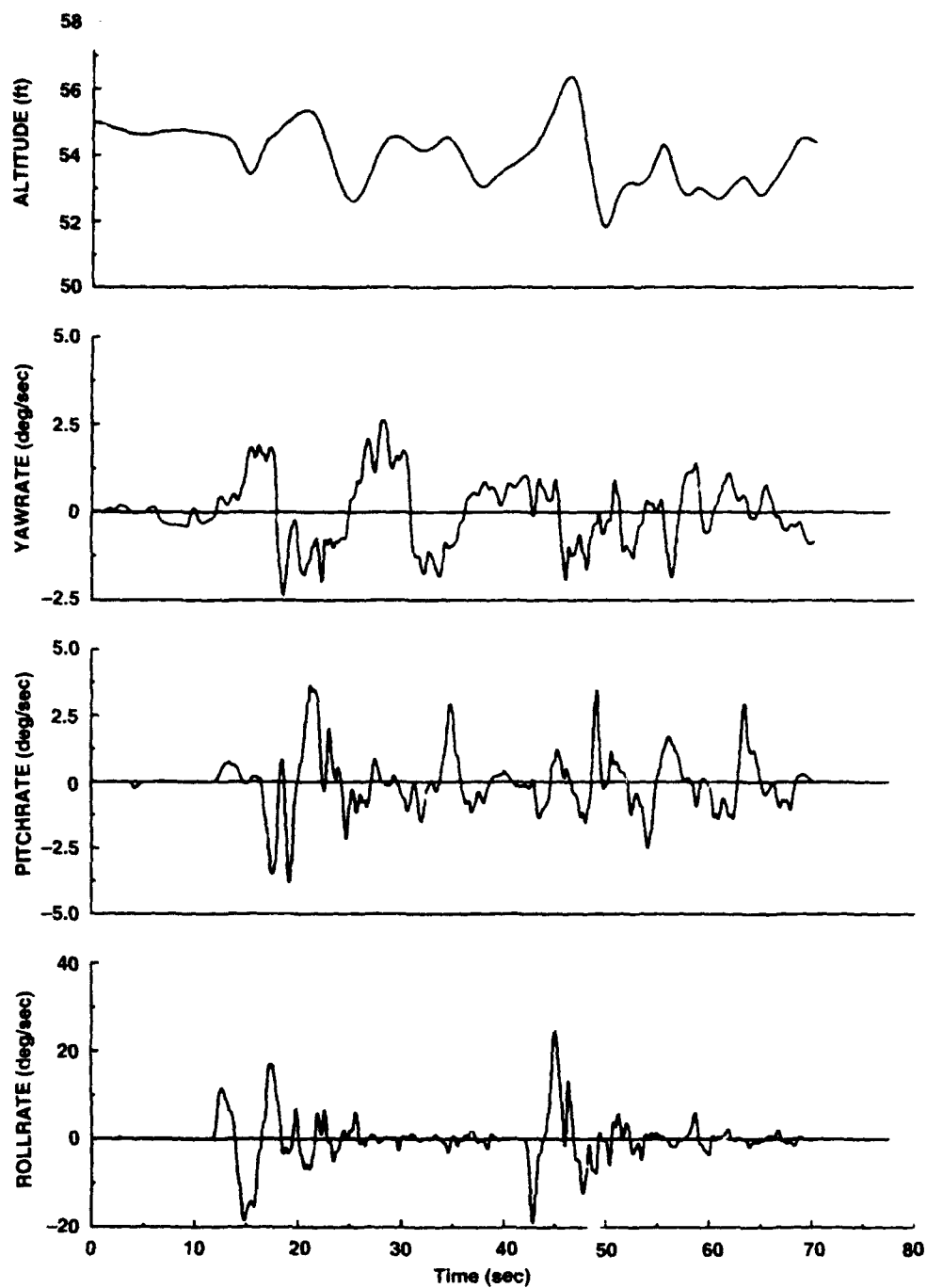
Figure 45. Pilot 4, side-step task (Continued). (e) Simulator (left to right).
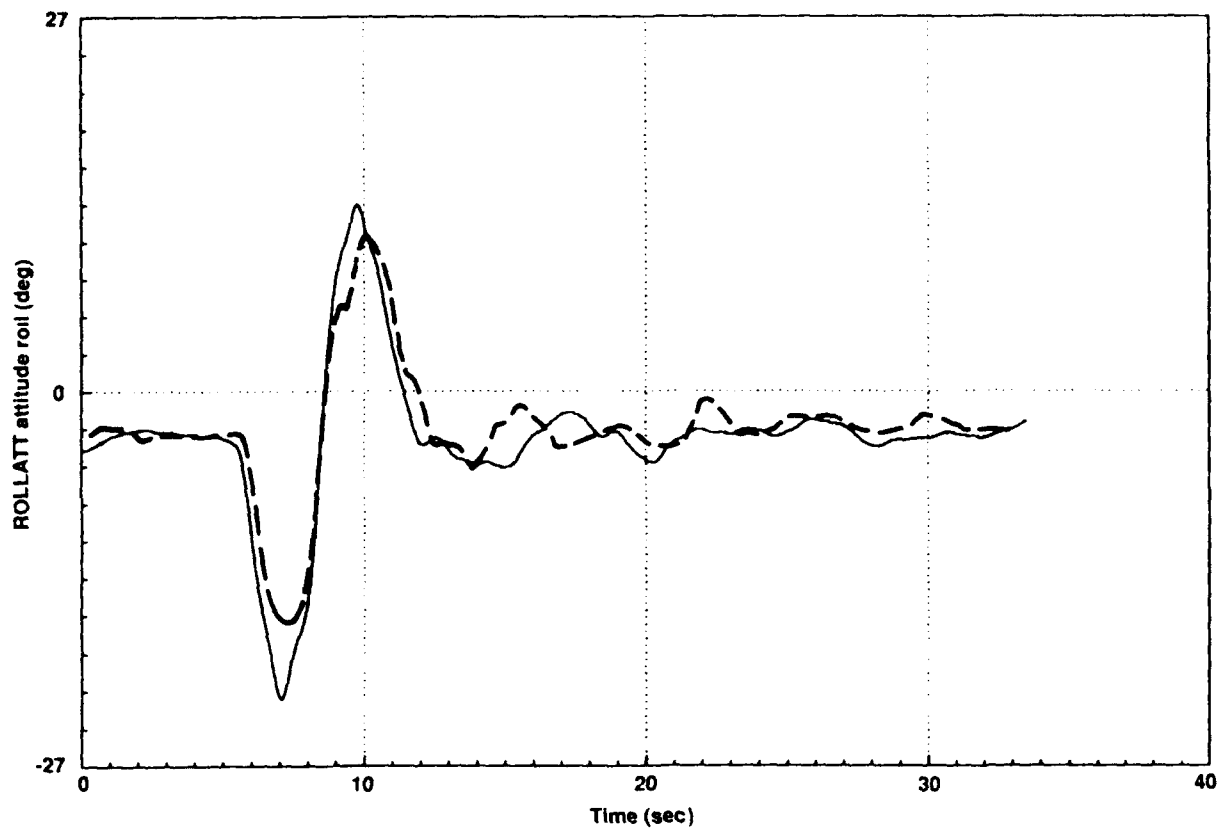
Figure 45. Pilot 4, side-step task (Concluded). (f) Flight versus simulator (right-to-left side step).

Variable	Flight[+]				Simulation[*]			
	min	max	avg	σ	min	max	avg	σ
Pitch attitude	7.25	12.42	9.44	0.83	1.33	5.76	3.6-	0.69
Pitch rate	-6.36	4.10	-0.20	1.37	-4.51	4.07	0.00	0.73
Roll attitude	-22.55	16.59	-3.15	5.68	-35.13	24.80	-2.71	6.91
Roll rate	-29.09	22.43	-0.31	6.45	-37.47	37.26	0.00	10.18
Yaw attitude	—	—	—	—	78.43	87.31	82.44	1.90
Yaw rate	-3.77	2.70	-0.14	1.21	-2.93	5.86	-0.09	1.02
Altitude	45.26	47.77	46.49	0.77	51.90	56.26	54.03	0.82

[+] for left-to-right side step   [*] for doublet

Variable	Flight[+]				Simulation[*]			
	min	max	avg	σ	min	max	avg	σ
Pitch attitude	4.84	12.08	7.69	1.42	0.00	6.06	3.63	1.00
Pitch rate	-4.51	5.95	-0.28	1.69	-3.83	3.66	-0.03	1.04
Roll attitude	-14.95	14.97	-2.78	4.81	-17.59	11.84	-2.71	4.33
Roll rate	-34.32	20.32	-0.44	4.89	-19.26	24.57	-0.01	4.99
Yaw attitude	—	—	—	—	85.53	91.25	86.46	2.00
Yaw rate	-4.79	5.84	-0.27	1.81	-2.38	2.61	0.00	0.93
Altitude	43.82	47.77	45.50	0.59	51.82	56.35	54.02	0.90

Attitudes are in degrees, rates are in degrees/sec, altitude is in ft.

Figure 46. Summary of data for side-step task.
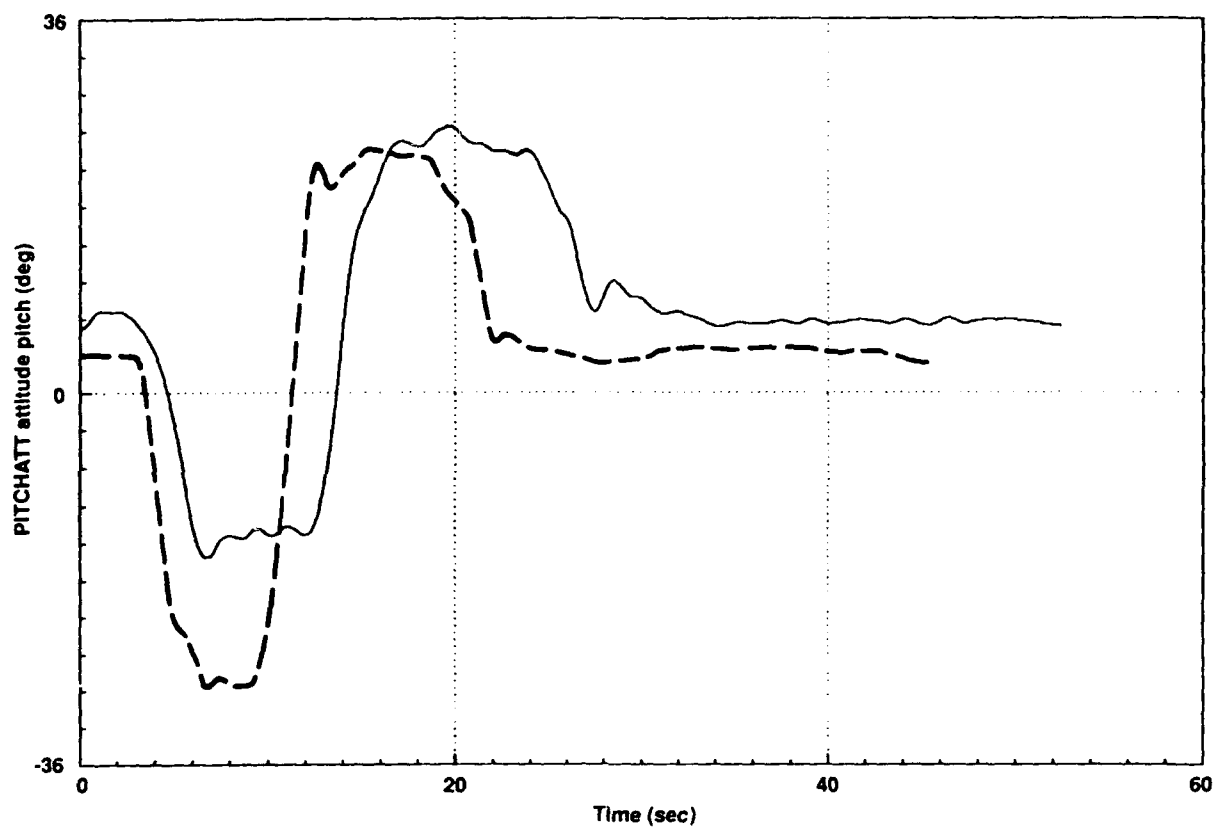
Figure 47. Pilot 2, dash/quick-stop task. (a) Flight versus simulator.
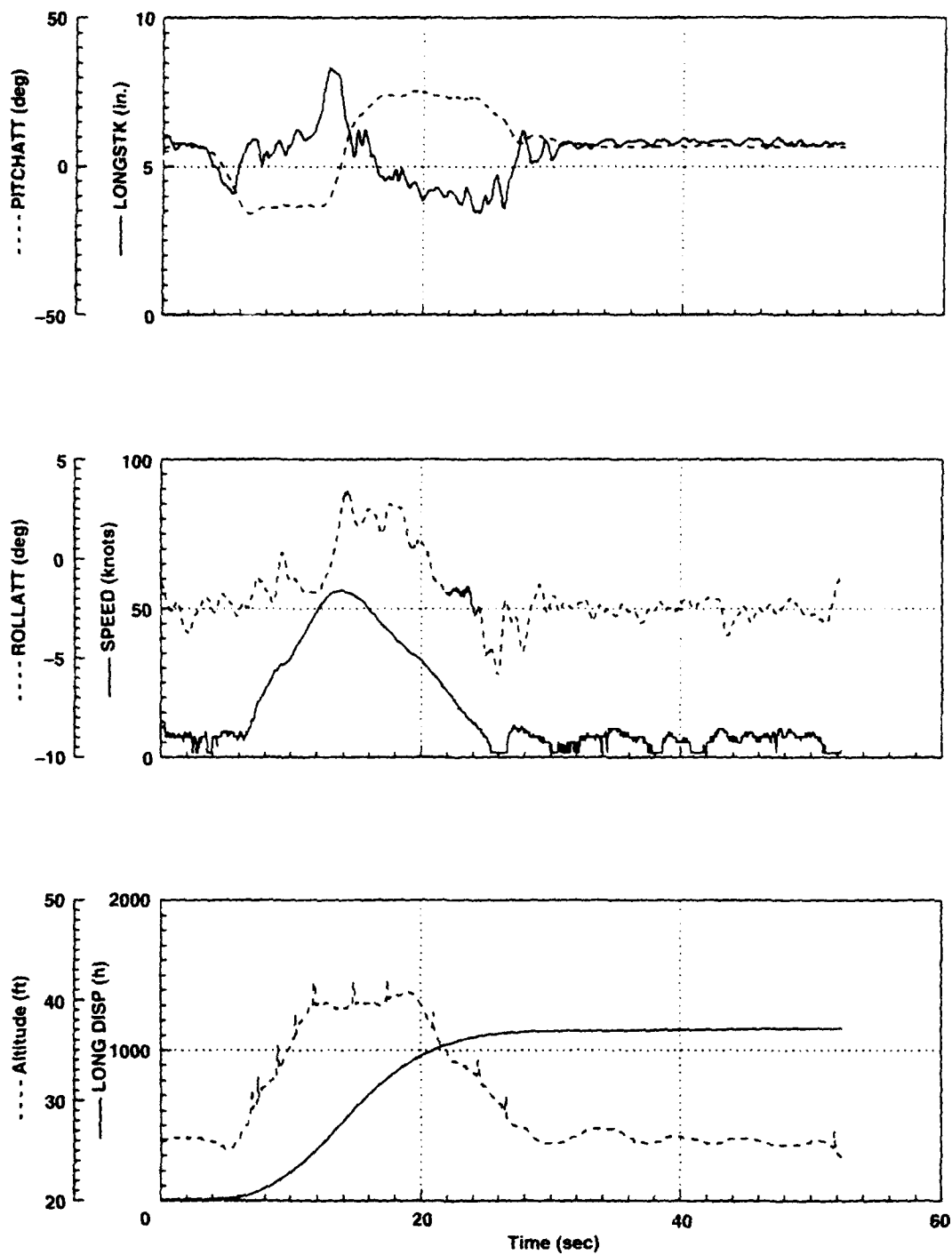
Figure 47. Pilot 2, dash/quick-stop task (Continued). (b) Flight data.
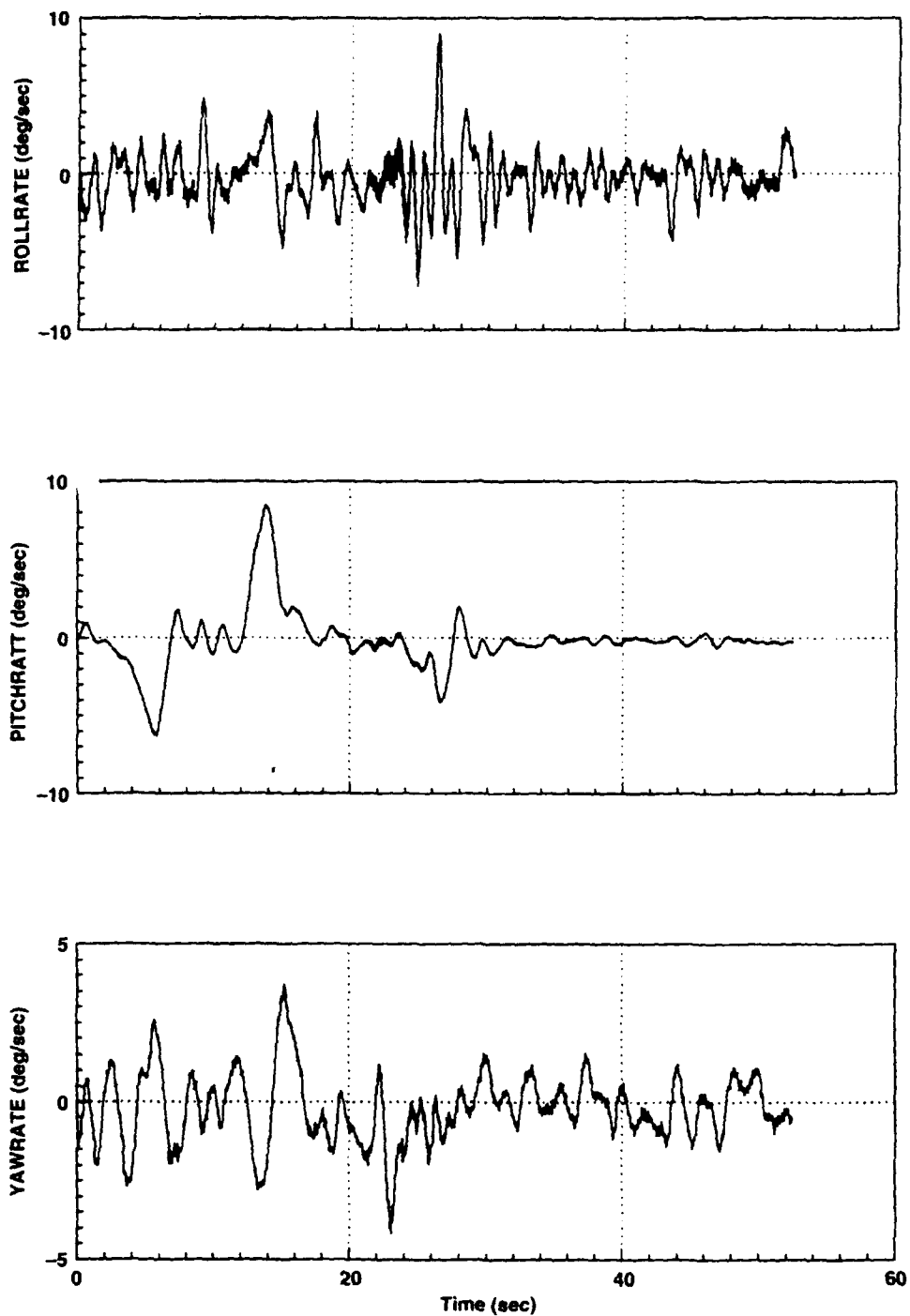
Figure 47. Pilot 2, dash/quick-stop task (Continued). (c) Flight data.
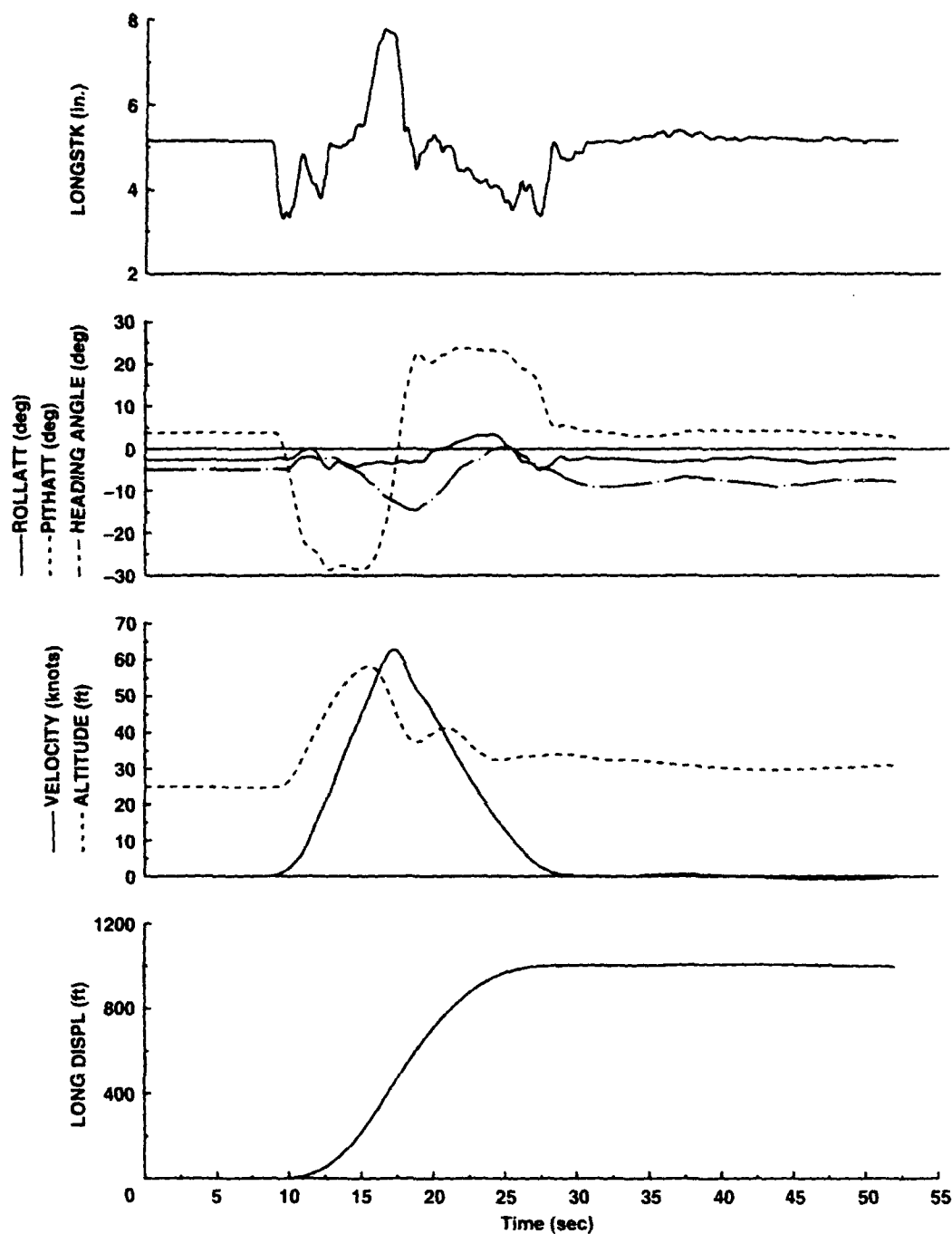
Figure 47. Pilot 2, dash/quick-stop task (Continued). (d) Simulator data.
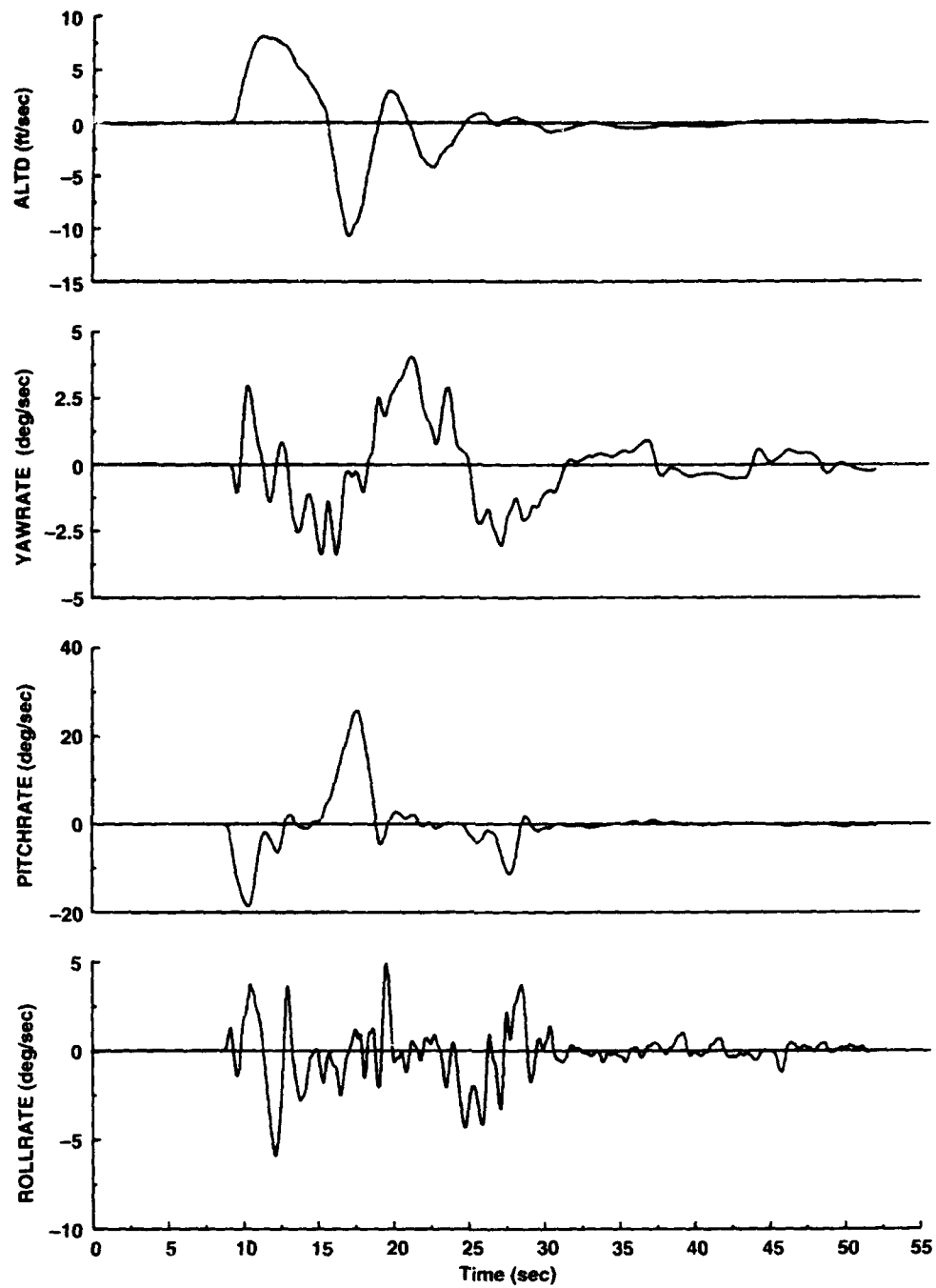
Figure 47. Pilot 2, dash/quick-stop task (Concluded). (e) Simulator data.
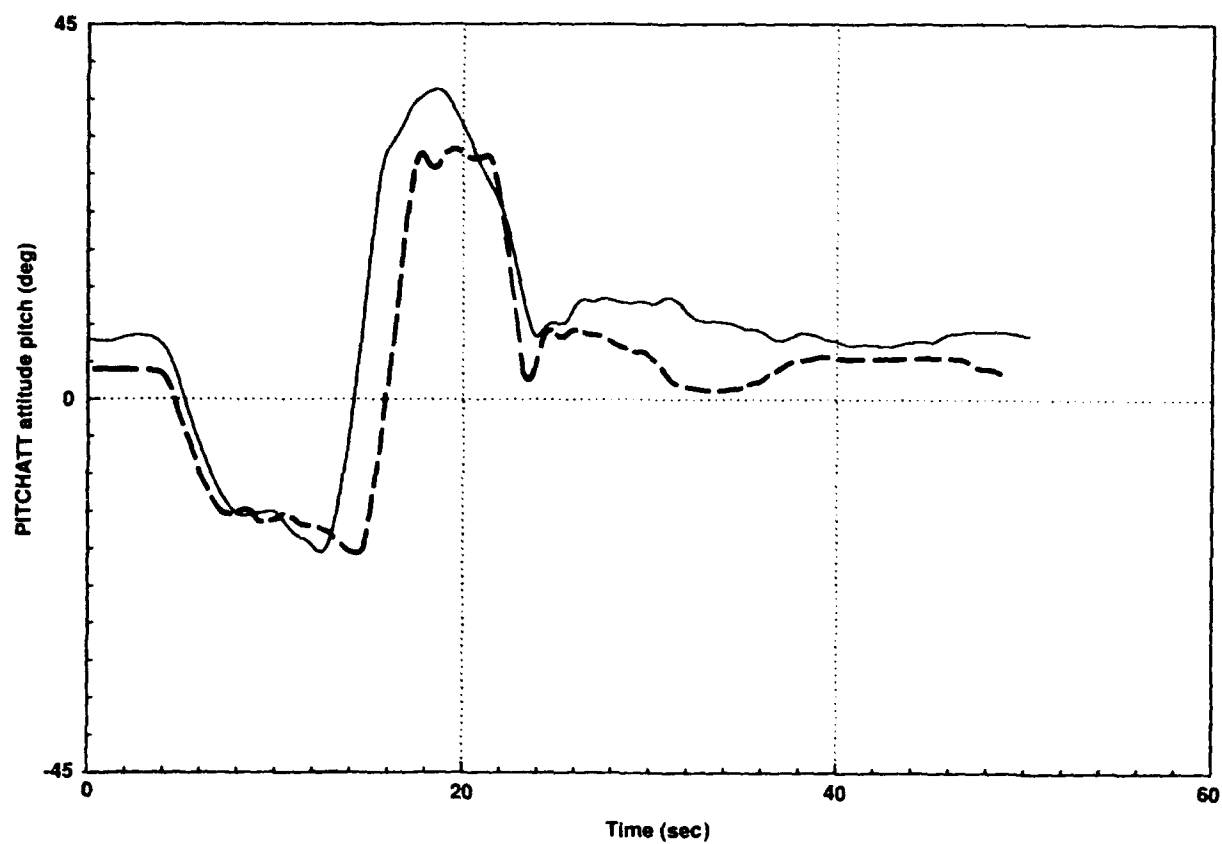
Figure 48. Pilot 4, dash/quick-stop task. (a) Flight versus simulator.
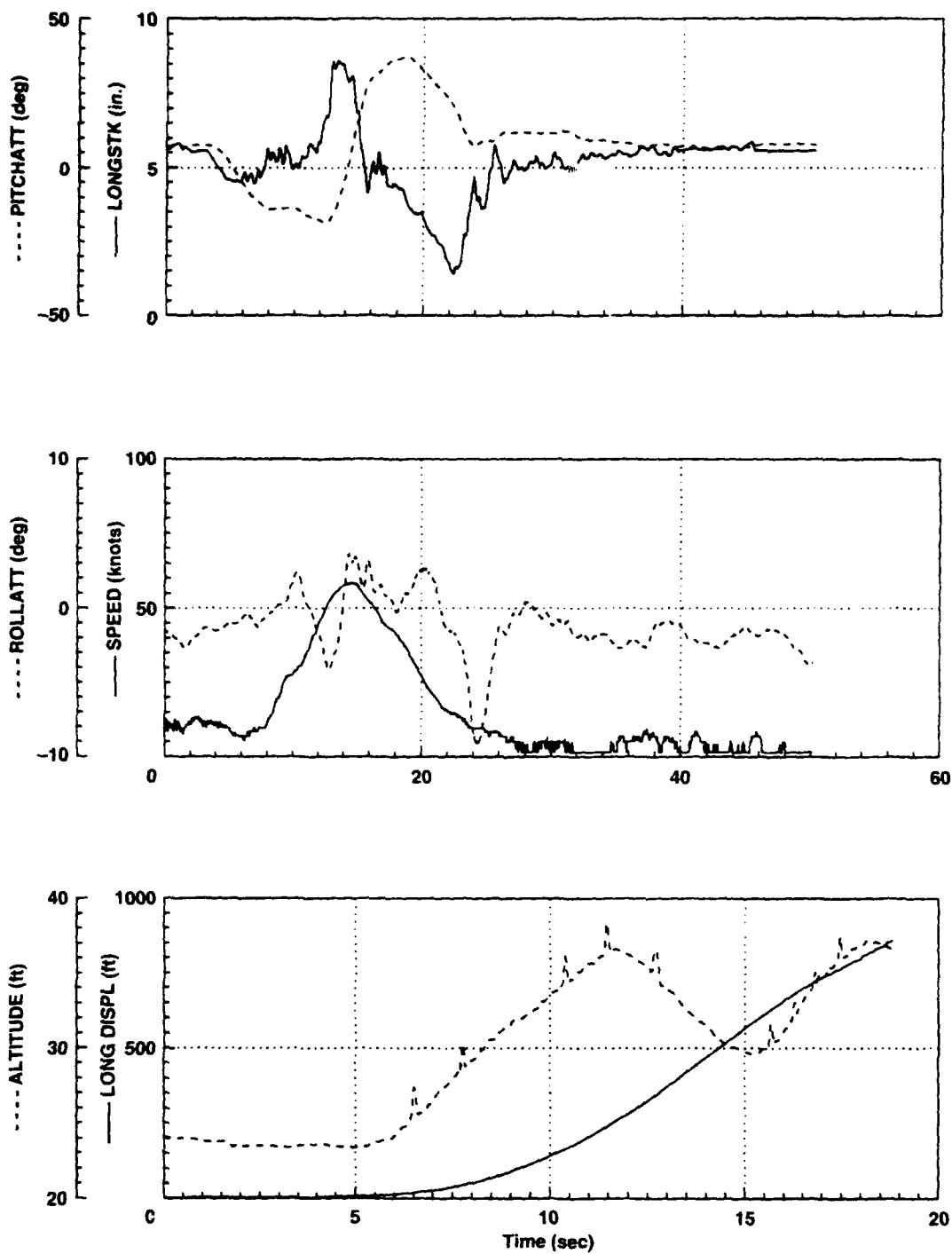
Figure 48. Pilot 4, dash/quick-stop task (Continued). (b) Flight data.
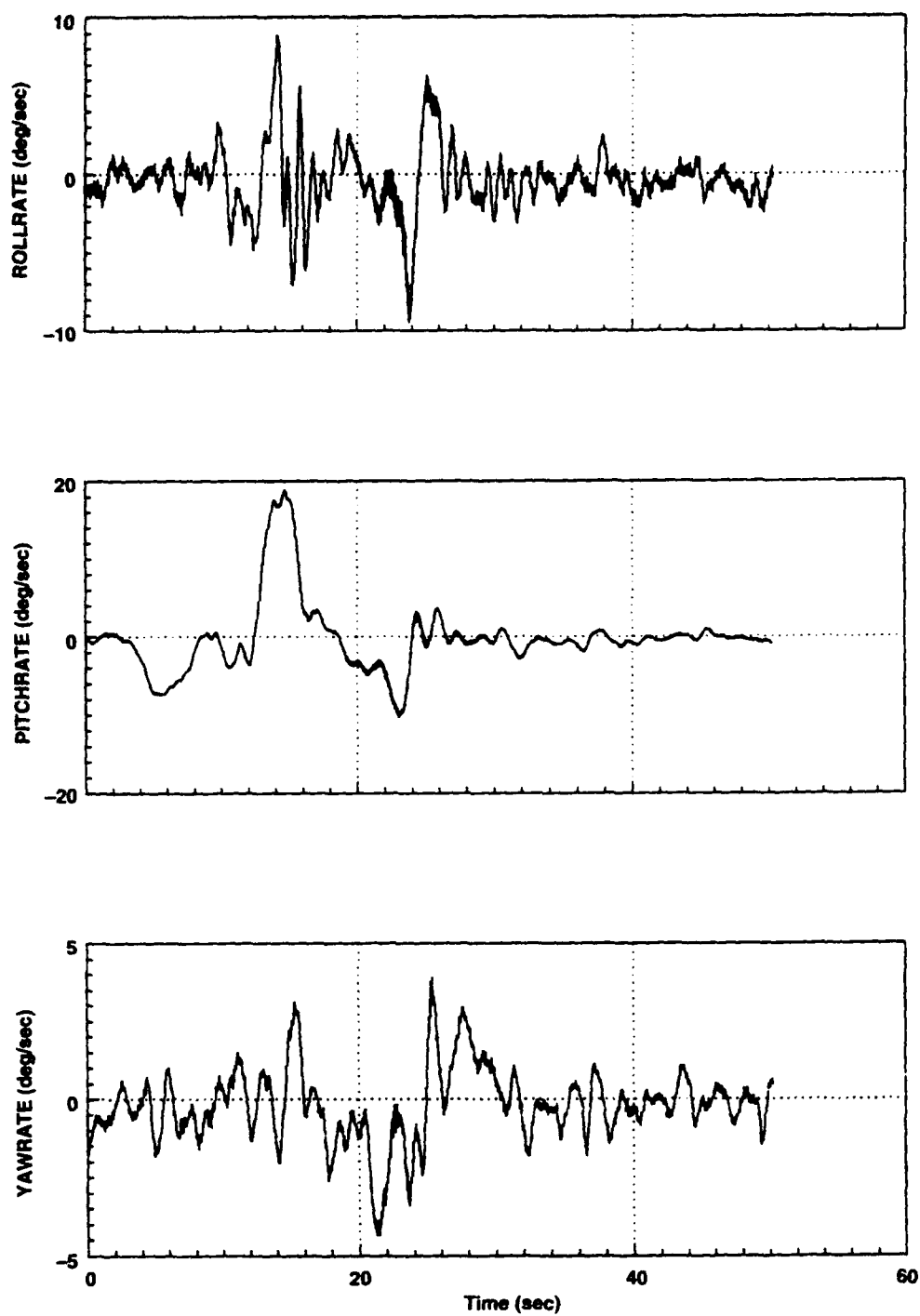
Figure 48. Pilot 4, dash/quick-stop task (Continued). (c) Flight data.

Figure 48. Pilot 4, dash/quick-stop task (Continued). (d) Simulator data.

113
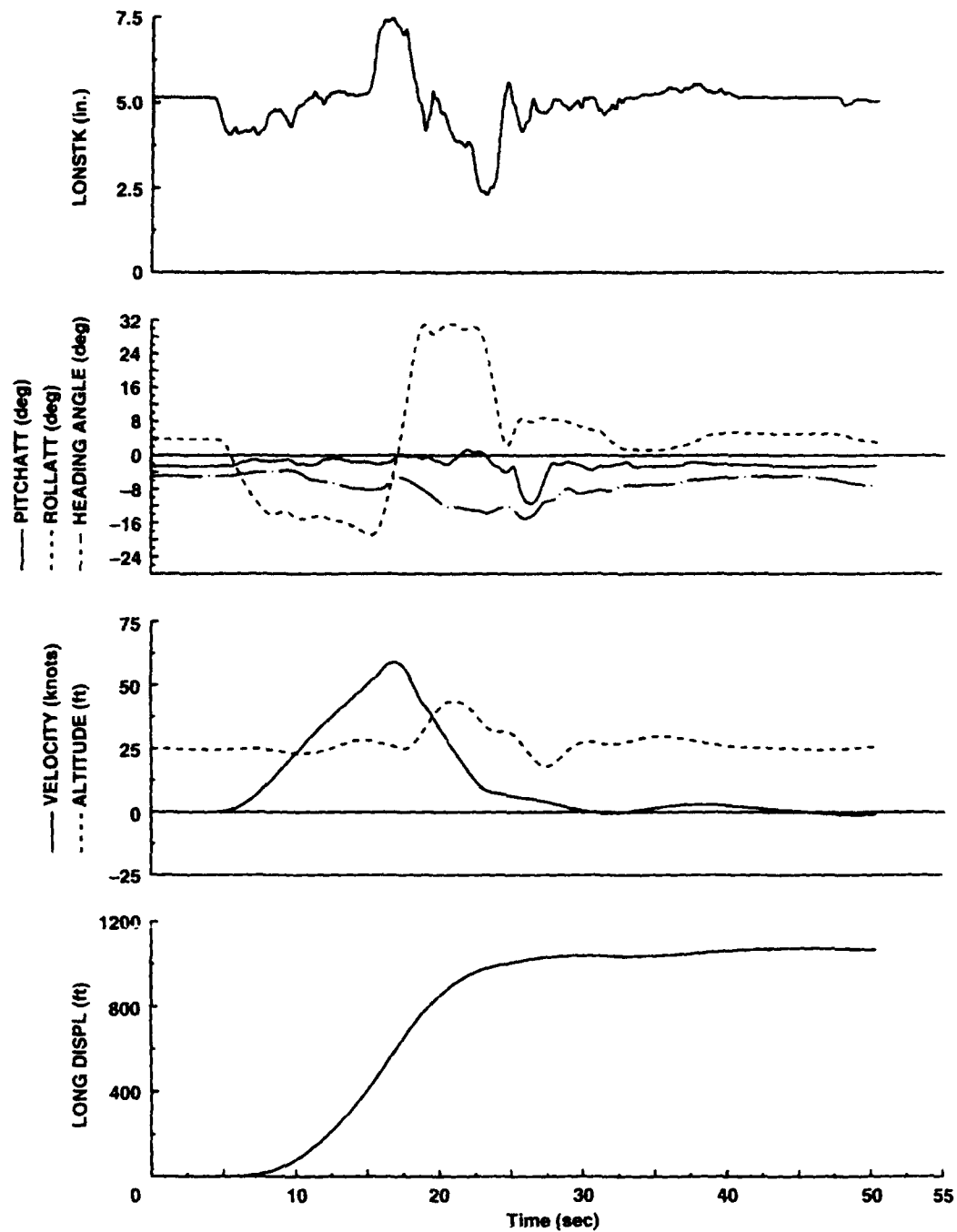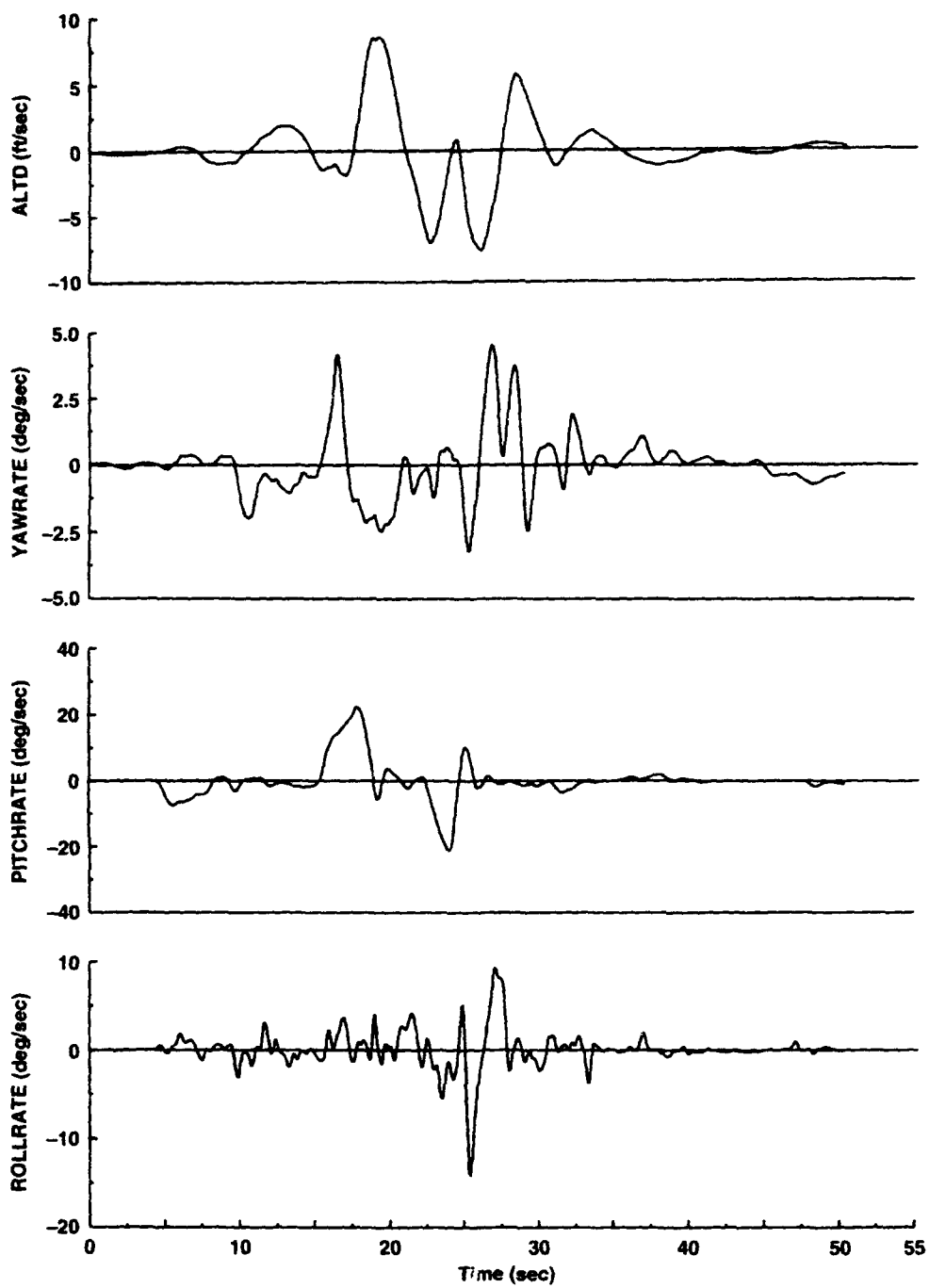
Figure 48. Pilot 4, dash/quick-stop task (Concluded). (e) Simulator data.

Pilot 2

Variable	Flight				Simulation			
	min	max	avg	σ	min	max	avg	σ
Pitch attitude	−15.76	25.68	7.35	10.90	−28.75	23.87	3.22	12.95
Pitch rate	−12.67	16.94	−0.33	3.70	−18.68	25.80	0.00	5.36
Roll attitude	−5.82	3.40	−1.75	1.69	−14.64	0.34	−6.55	3.01
Roll rate	−7.25	9.05	−0.27	1.73	−5.92	4.96	−0.14	1.32
Yaw attitude	—	—	—	—	−14.64	0.34	−6.55	3.01
Yaw rate	−4.19	3.72	−0.21	1.10	−3.40	4.04	−0.04	1.29
Altitude	31.97	59.26	40.61	7.47	24.72	58.25	33.30	7.90

Pilot 4

Variable	Flight				Simulation			
	min	max	avg	σ	min	max	avg	σ
Pitch attitude	−18.44	37.18	8.13	12.79	−18.88	31.06	3.31	12.06
Pitch rate	−10.26	18.88	−0.26	4.54	−21.17	22.46	−0.03	5.40
Roll attitude	−9.08	3.67	−1.24	1.98	−11.45	1.29	−2.31	1.74
Roll rate	−9.47	8.85	−0.42	2.03	−14.22	9.36	0.05	2.10
Yaw attitude	—	—	—	—	−15.02	−3.61	−7.22	2.82
Yaw rate	−4.37	3.90	−0.21	1.17	−3.25	4.45	−0.05	1.13
Altitude	31.61	59.26	39.21	7.75	17.95	43.62	27.06	4.68

Attitudes are in degrees, rates are in degrees/sec, altitude is in ft.

Figure 49. Summary of data for dash/quick-stop task.

High: Motion sensations are close to those of visual flight
Medium: Motion sensation differences are noticeable but not objectionable
Low: Differences are noticeable and objectionable, loss of performance, disorientation from Sinacori [41]
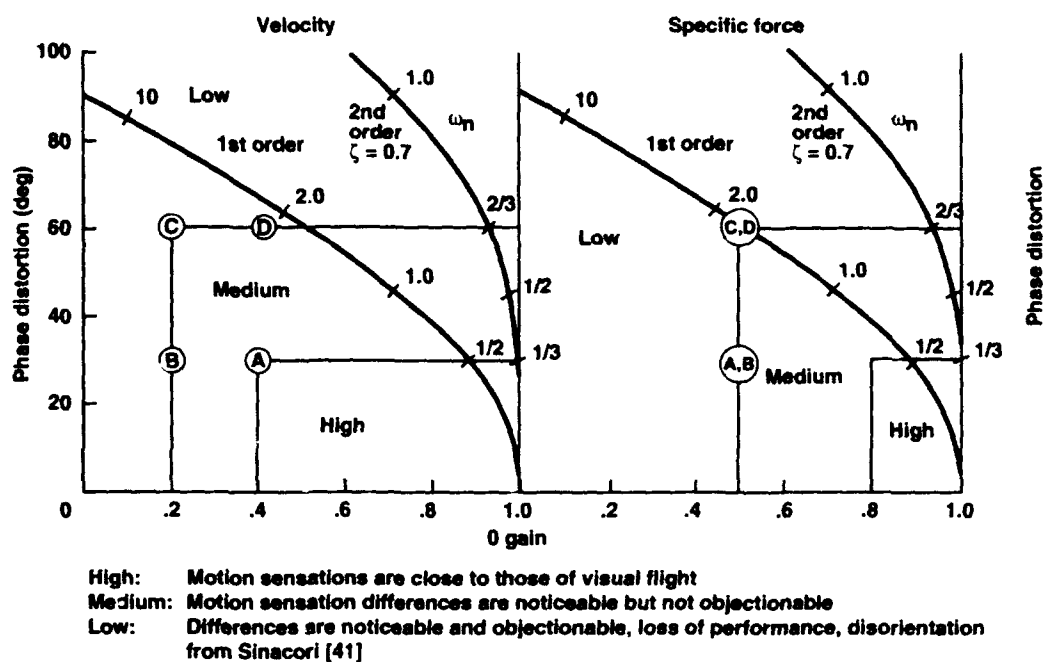
Figure 50. Fidelity of motion plot (ref. 41).
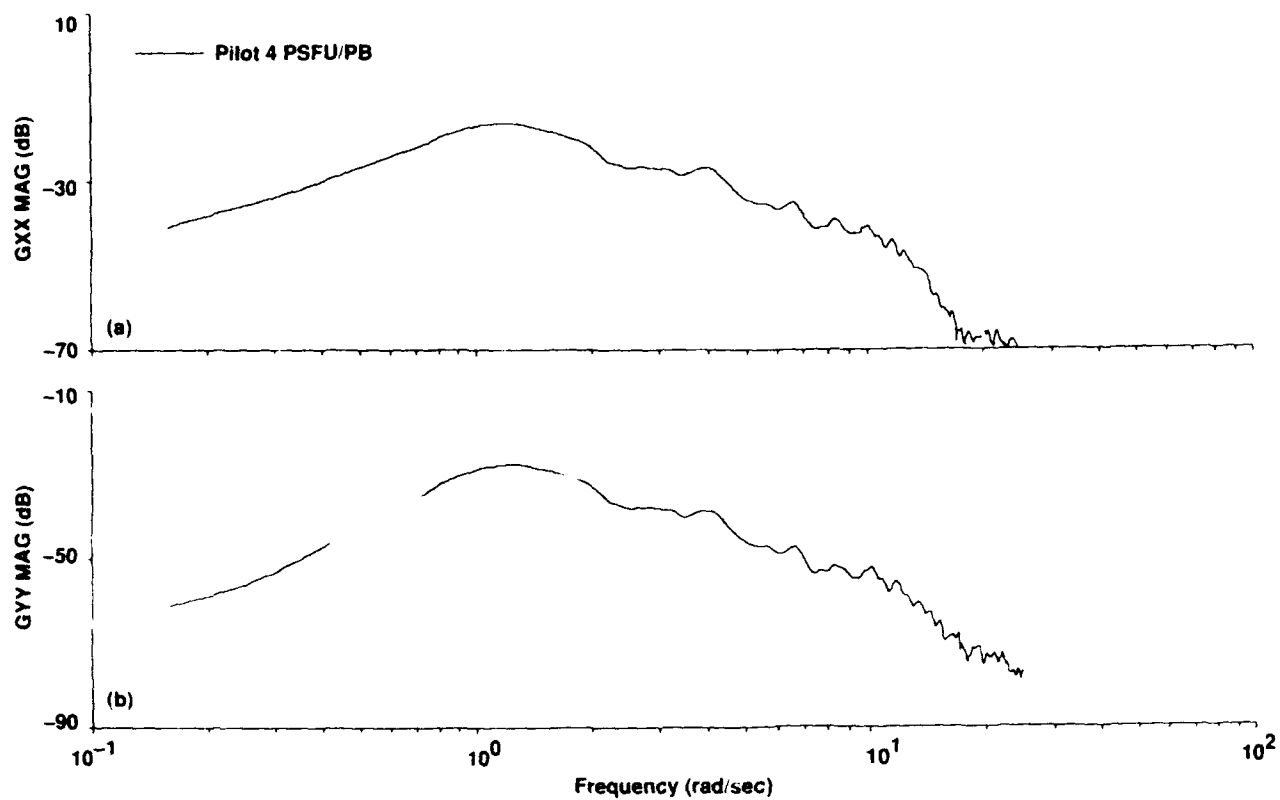
Figure 51. Input and output power spectra for PB and PSFU for the side-step task.
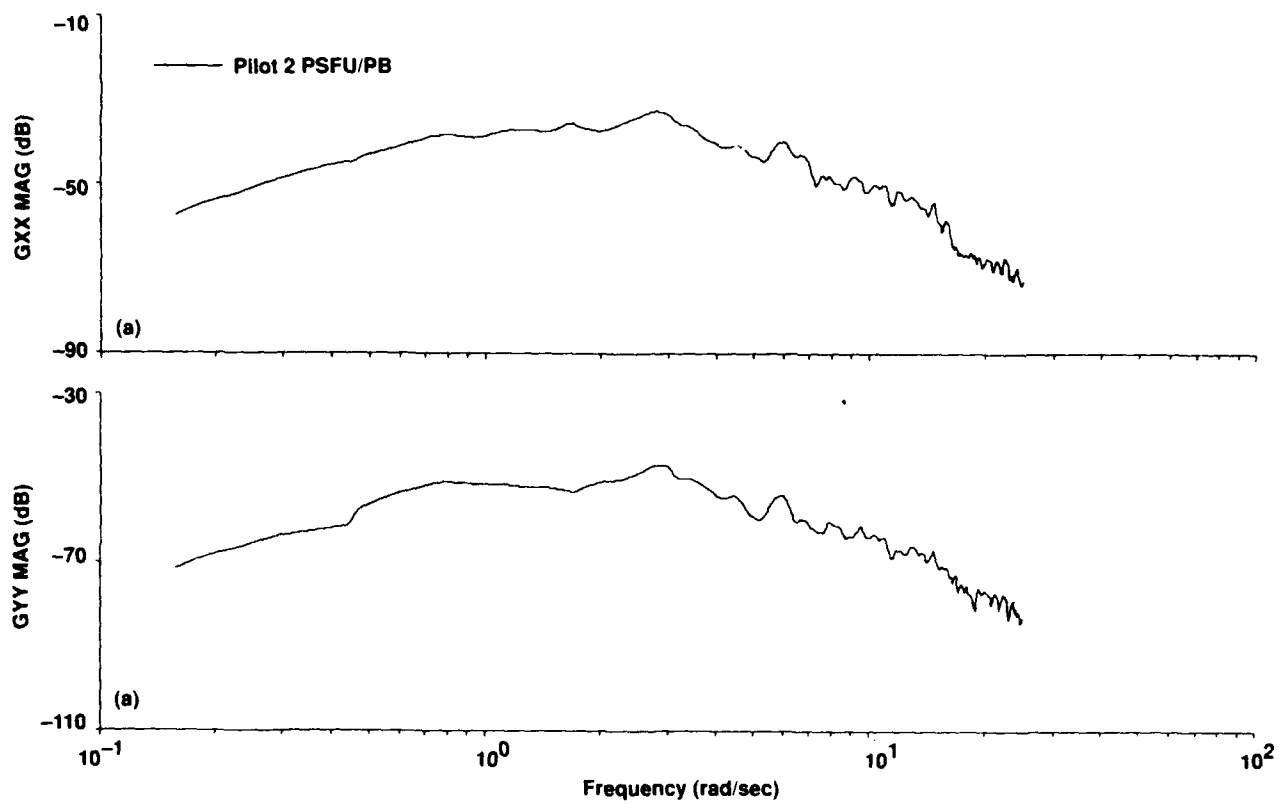
Figure 52. Input and output power spectra for PB and PSFU for the bob-up task.

	Pilot 2			Pilot 4			Pilot 5			High fidelity motion range (rad/sec)*
	BU	SS	DQS	BU	SS	DQS	BU	SS	DQS	
Roll rate	2.8 4.7 3.9 (1.81)	4.9 3.8 5.0	4.5 3.5 3.5	5.6 5.9 4.8 (1.48)	5.0 3.8 4.5	4.6 4.5 5.0	4.3 5.0 4.2	3.1 4.5 3.1 (1.26)	5.2 5.8 4.7	2.6 ‾‾‾ 1.8 - 4.0
Pitch rate	3.1 2.5 3.4	2.5 3.8 3.1 (0.54)	4.2 2.7 3.8	3.7 3.5 3.8	3.1 2.5 3.7	3.0 2.2 2.8 (0.47)	3.8 3.1 3.8	3.2 3.8 3.8	3.1 3.1 3.1 (0.51)	2.2 ‾‾‾ 1.6 - 3.0
Yaw rate	3.4 3.3 3.1	3.1 2.6 2.8	3.7 2.9 2.8	2.9 2.4 2.8	3.9 3.1 3.1	3.3 2.9 2.8	2.8 3.0 3.3	4.2 3.7 4.2	3.4 3.5 5.0	2.4 ‾‾‾ 0.6 - 3.8
Heave rate	2.7 1.9 2.5 (1.29)	2.1 1.8 1.7	1.7 1.0 1.6	2.2 2.3 2.1 (1.48)	1.3 1.7 1.5	1.6 1.0 1.6	2.2 1.1 2.2 (0.88)	1.6 2.2 1.7	0.8 1.3 0.8	1.1 ‾‾‾ 0.9 - 1.6

* Determined for ± 20° phase distortion range from Bode Plots.

◯ = pilot cutoff frequency (rad/sec) for task - determined from input auto spectra.

Note: Data used in this matrix is from time history data from the mathematical model. The frequencies tabulated are the rate of change of the commanded rate input to the simulator motion system.

Figure 53. Summary of rate of change of commanded rate to the simulator motion system.
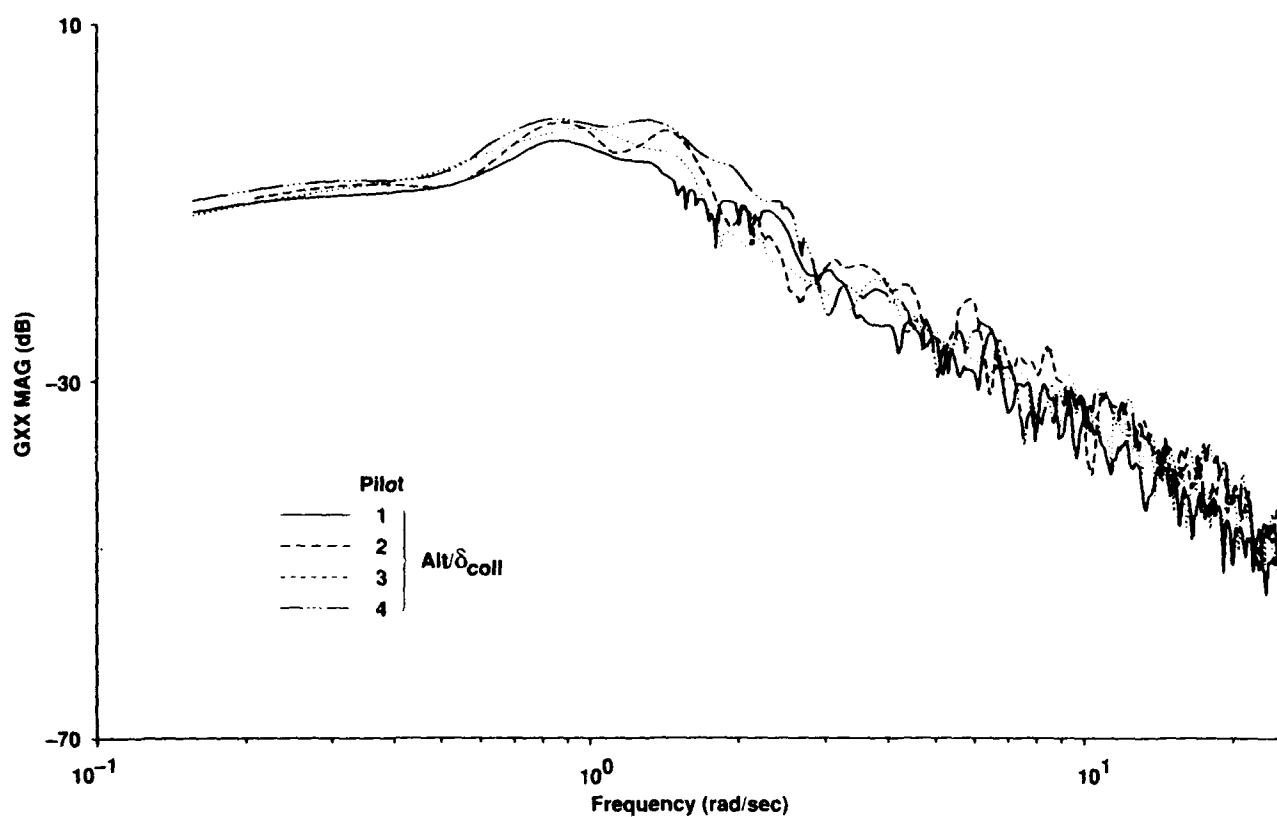
Figure 54. Input power spectra for four pilots in flight test—bob-up task.
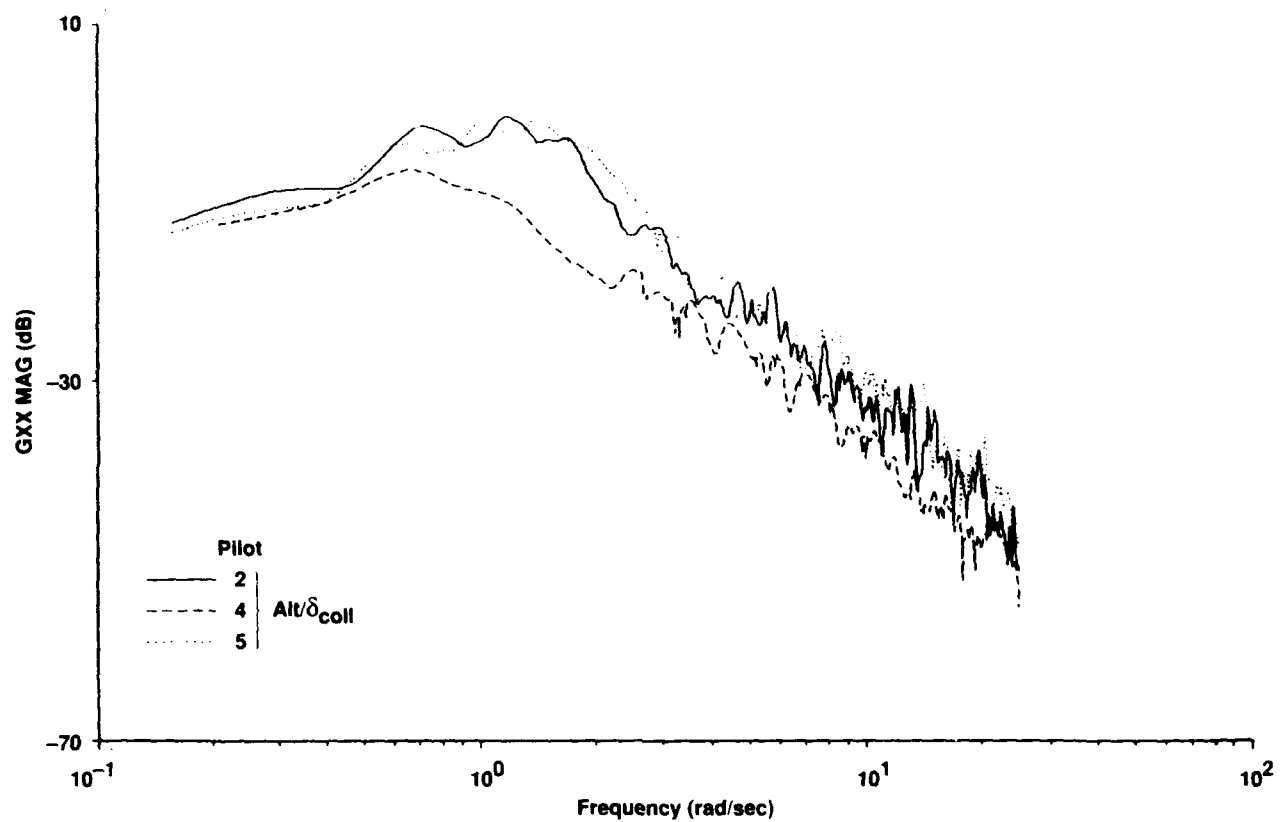
Figure 55. Input power spectra for three pilots in simulator—bob-up task.
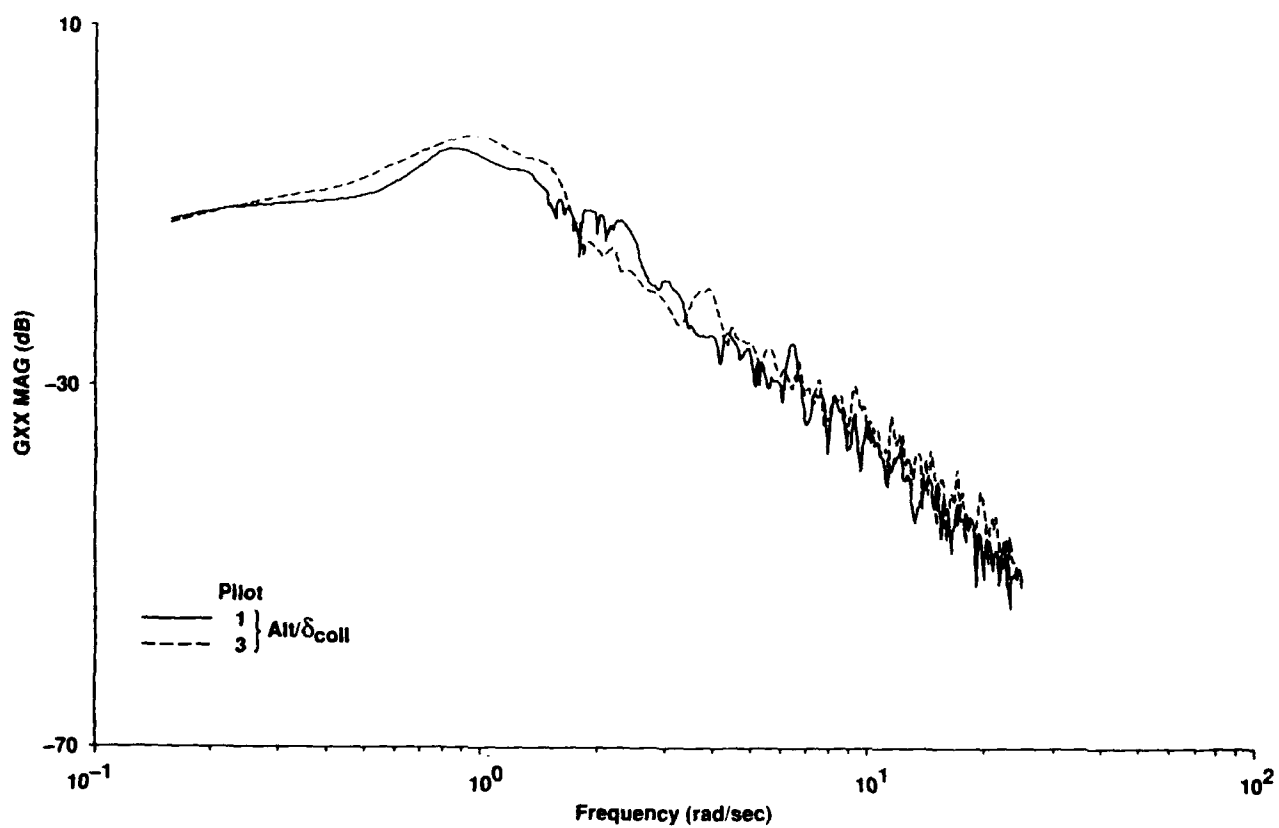
Figure 56. Comparison of input power spectra for two experienced pilots—flight, bob-up task.
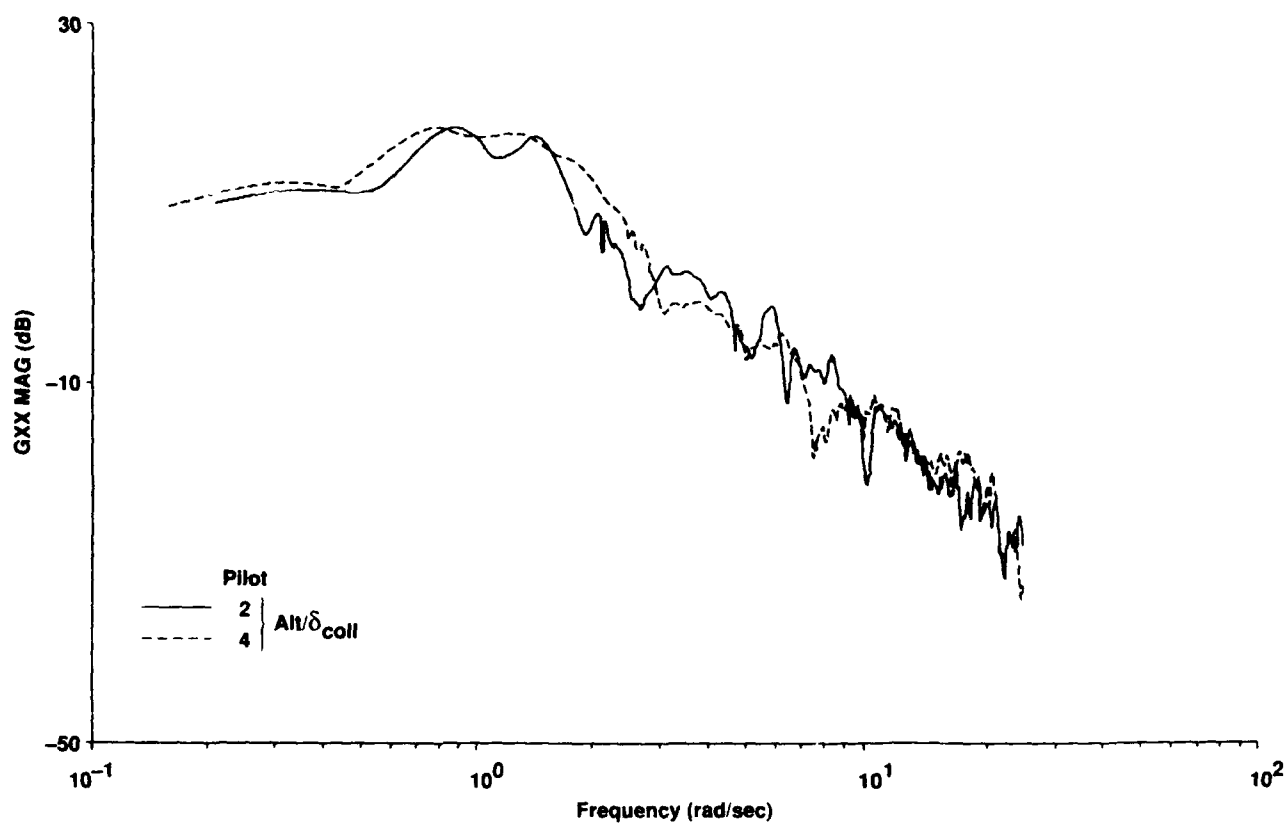
Figure 57. Comparison of two inexperienced pilots—flight, bob-up task.

Task	Pilot 1		Pilot 2		Pilot 3		Pilot 4		Pilot 5	
	ω_c	ψ	ω_c	ψ	ω_c	ψ	ω_c	ψ	ω_c	ψ
Bob-up/Bob-down										
Flight	1.05	0.383	1.15	0.472	1.04	0.445	1.20	0.564		
Simulator			1.26	0.544			1.43	0.579	0.876	0.251
FPS = on			1.32	0.543			1.29	0.563	0.850	0.267
Side step										
Flight	1.33	0.559	1.29	0.487	1.16	0.475	1.25	0.536		
Simulator			1.81	0.651			1.48	0.436	1.26	0.226
FPS = on			1.68	0.639			1.36	0.405	1.29	0.301
Dash/quick-stop										
Flight	0.500	0.799	0.440	0.713	0.460	0.935	0.450	1.03		
Simulator			0.535	0.757			0.470	0.810	0.510	0.714

Note: Values are for FPS = off unless otherwise noted.

Figure 58. Summary of pilot cut-off frequency and root mean square values.
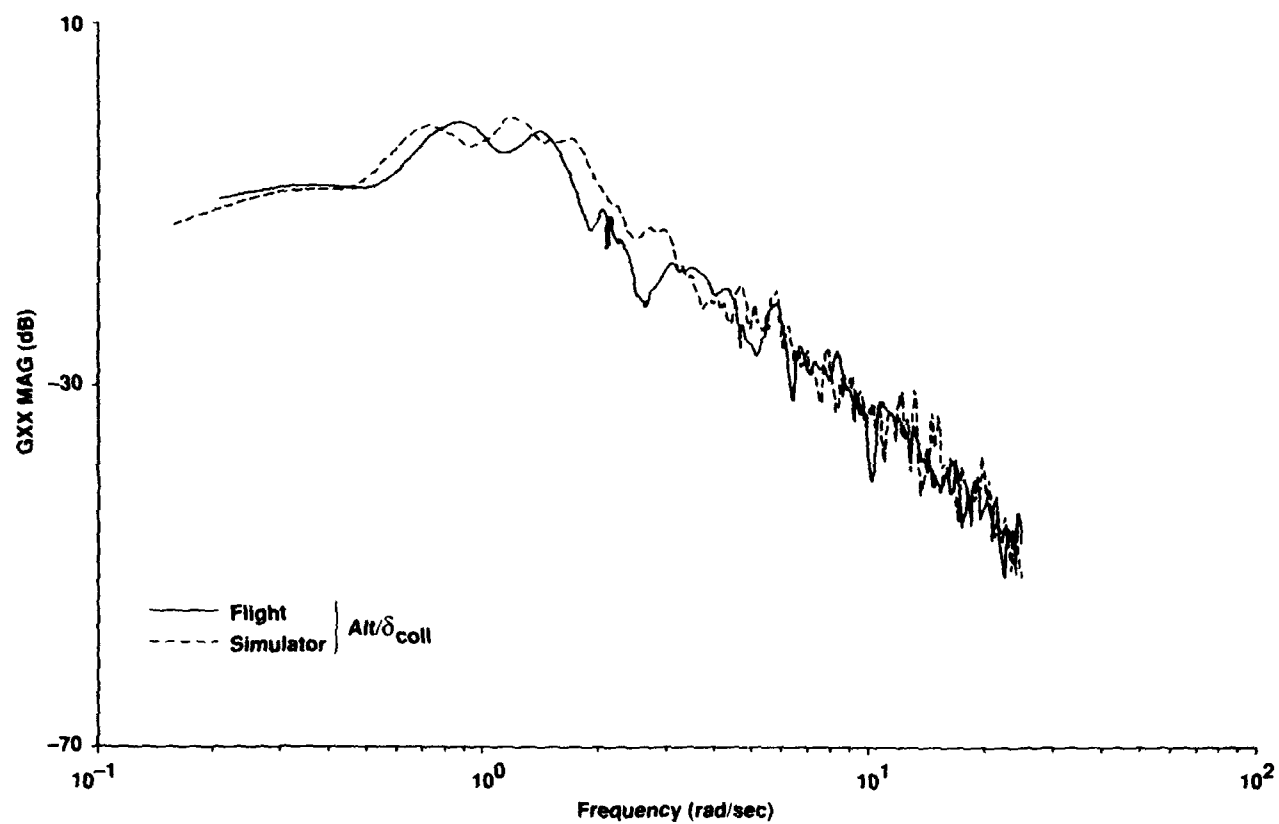
Figure 59. Pilot 2: input power spectra for flight versus simulator, bob-up task.
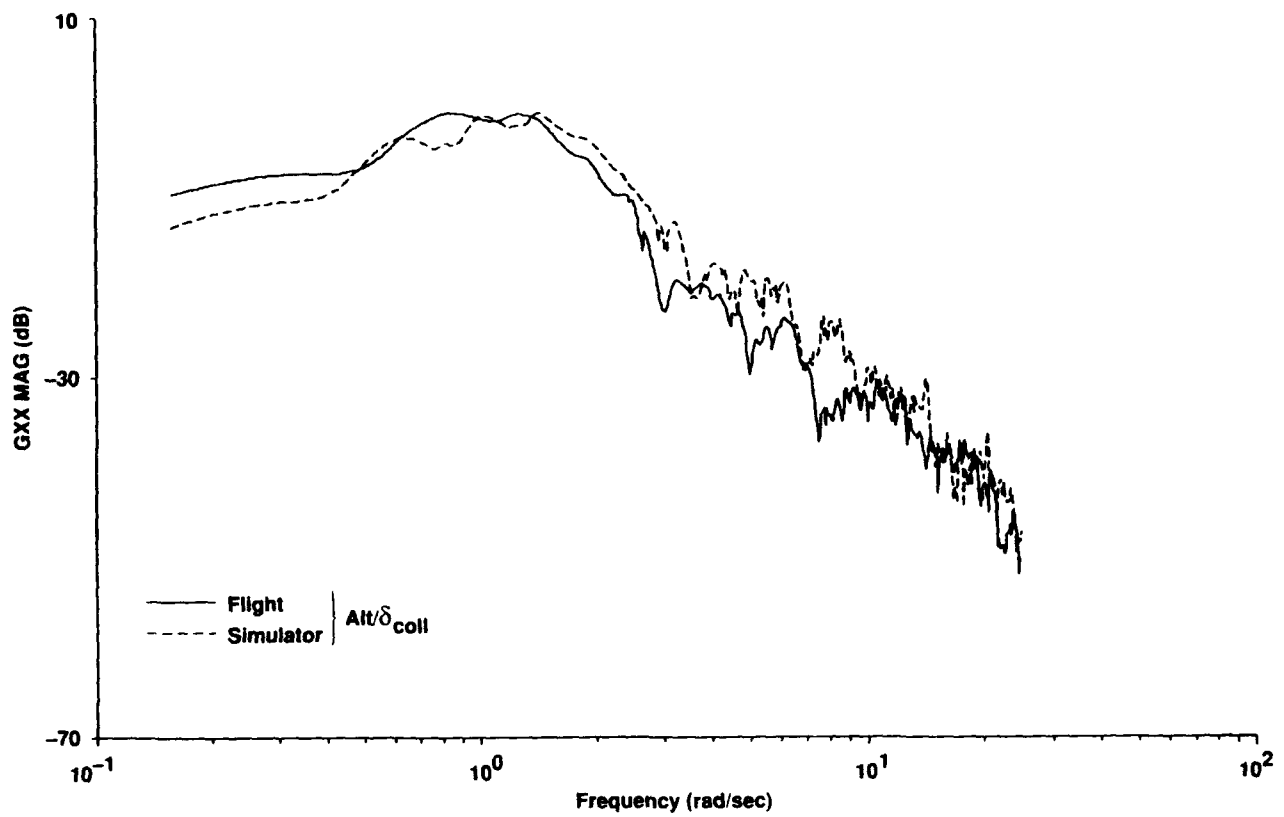
Figure 60. Pilot 4: input power spectra for flight versus simulator, bob-up task.
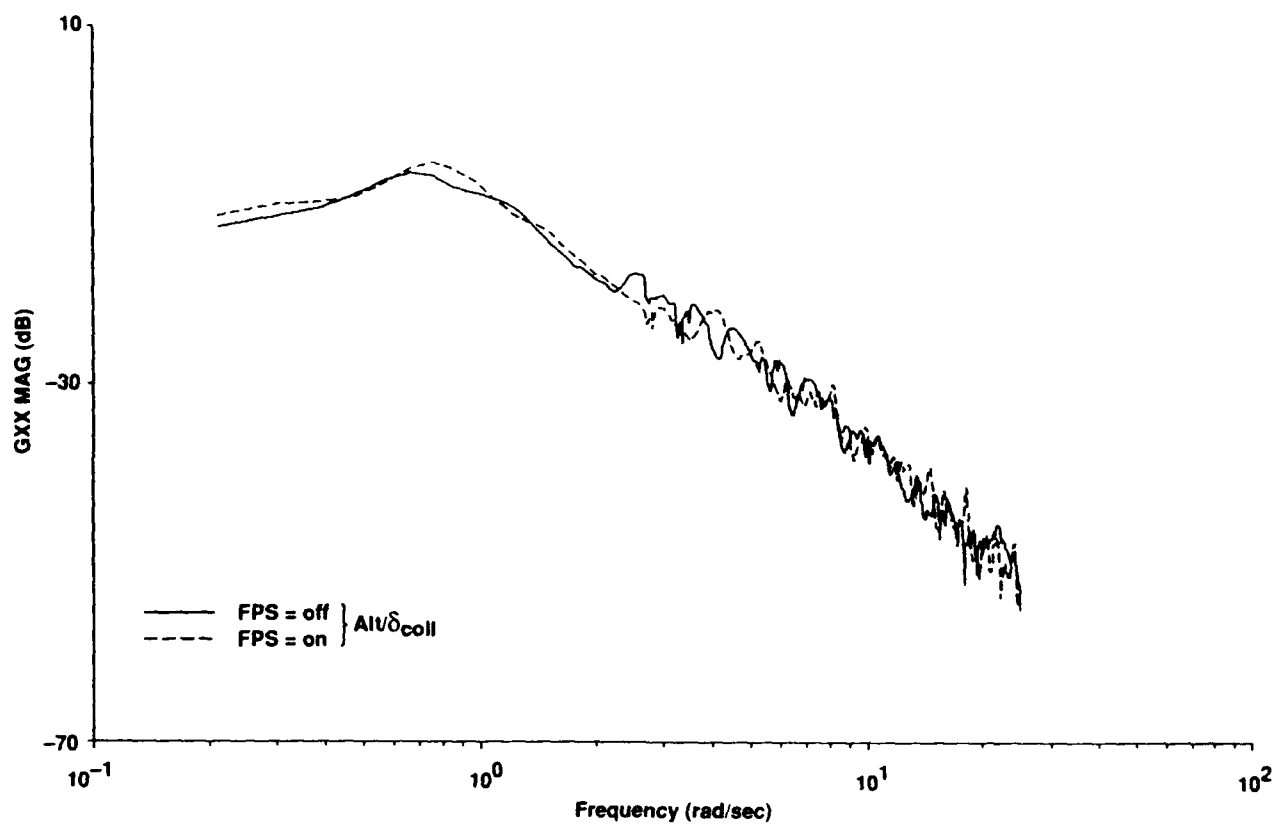
Figure 61. Pilot 5: input power spectra for simulator bob-up, FPS off versus FPS on.
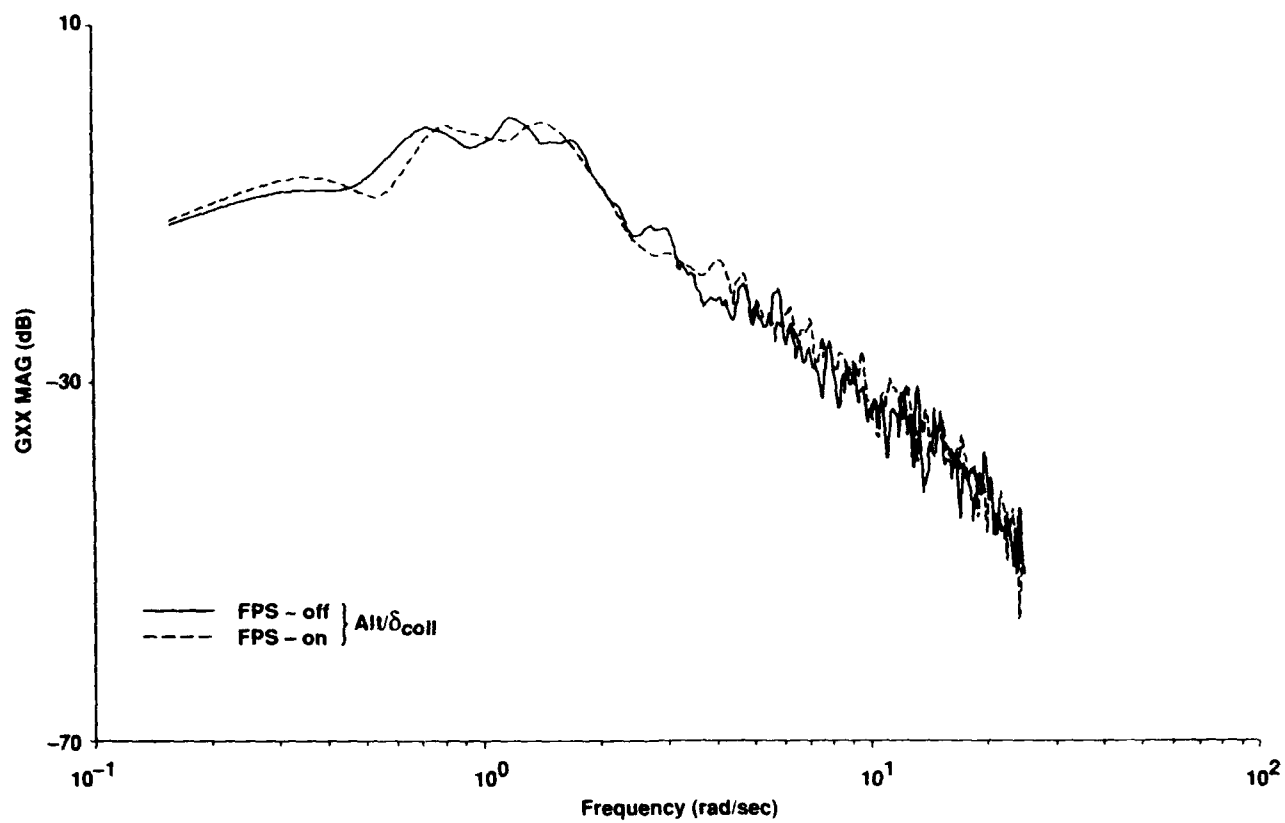
Figure 62. Pilot 2: input power spectra for simulator bob-up, FPS off versus FPS on.
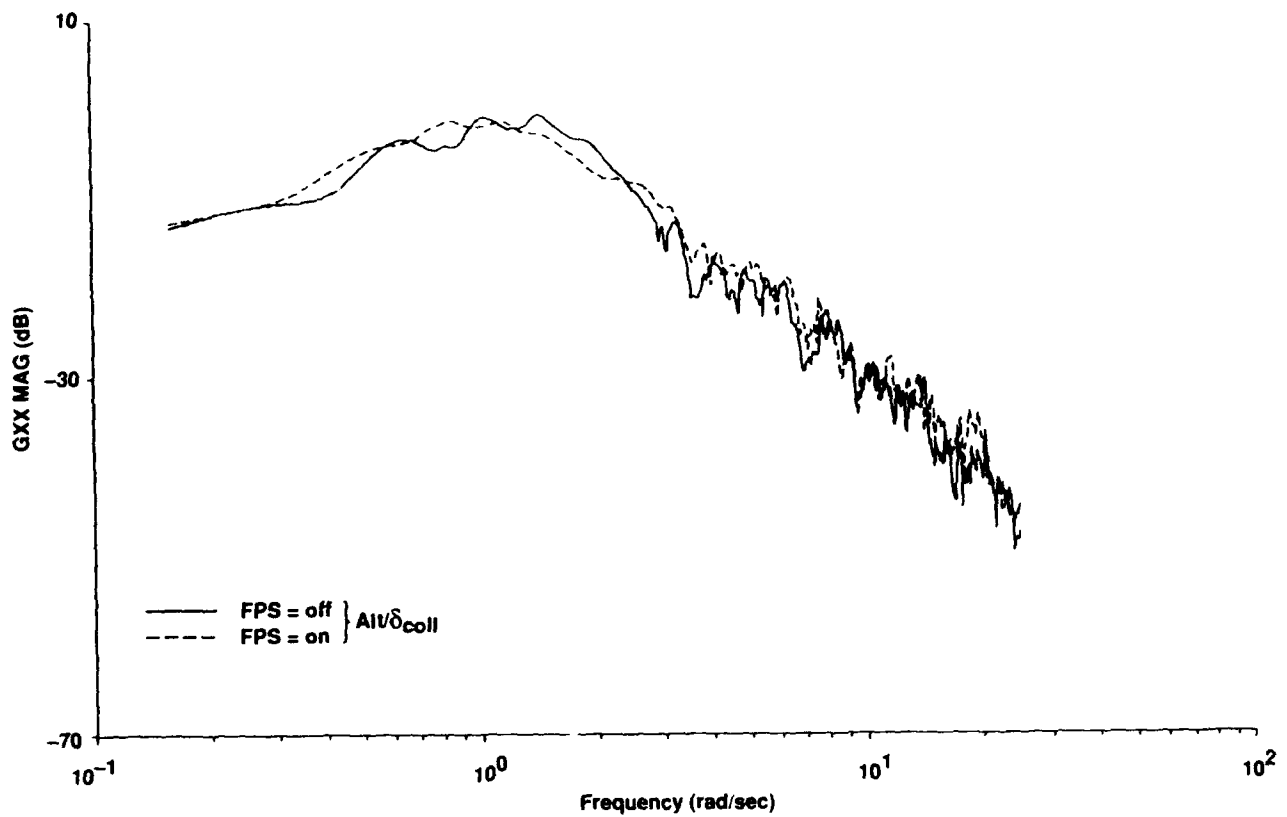
Figure 63. Pilot 4: input power spectra for simulator bob-up, FPS off versus FPS on.
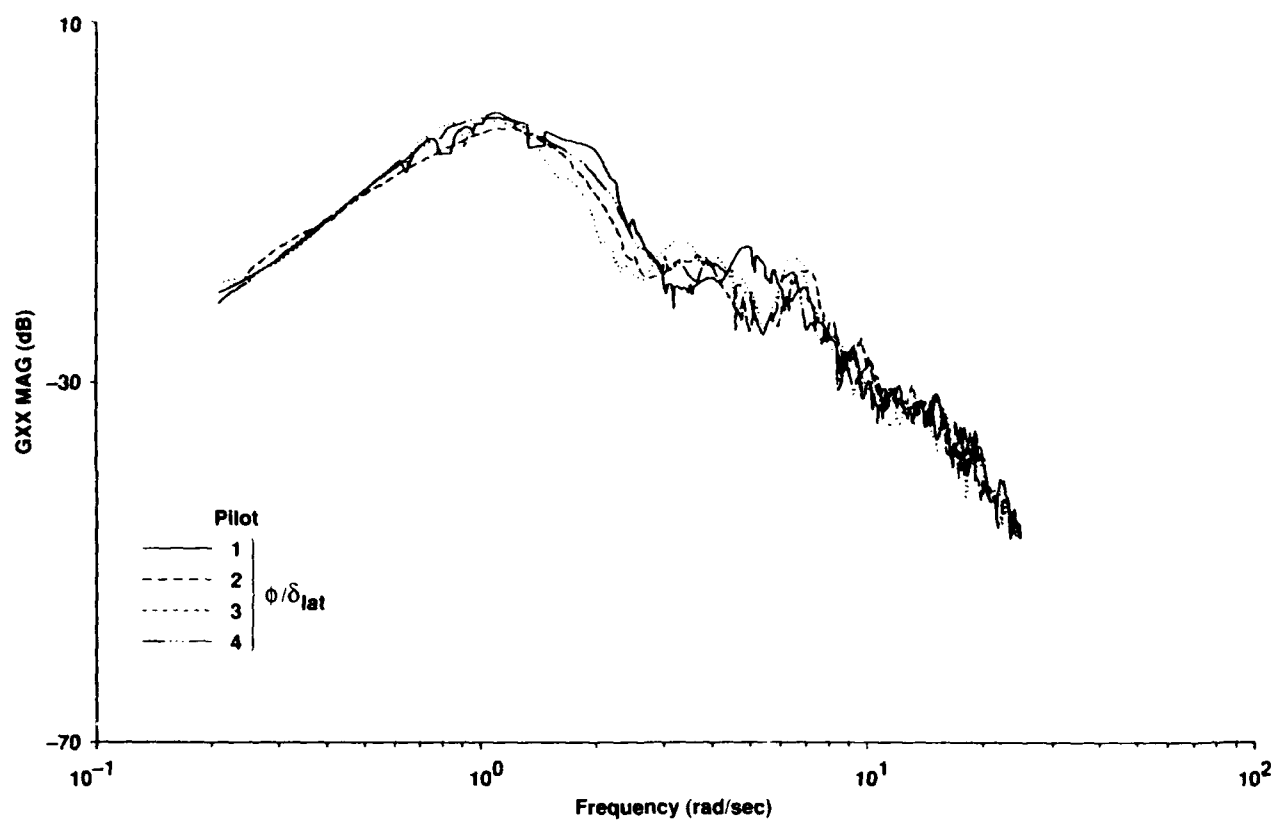
Figure 64. Input power spectra for four pilots in flight, side-step maneuver.
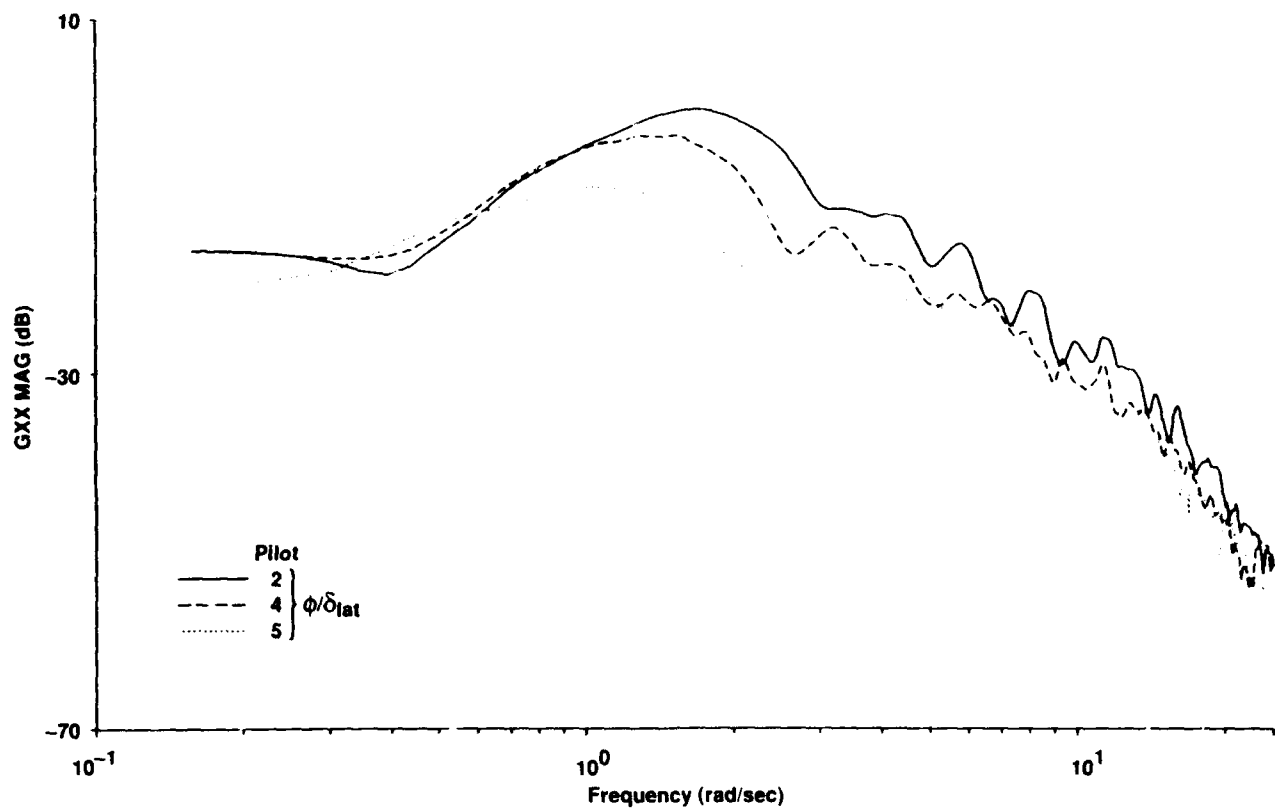
Figure 65. Input power spectra for three pilots in simulator, side-step maneuver.
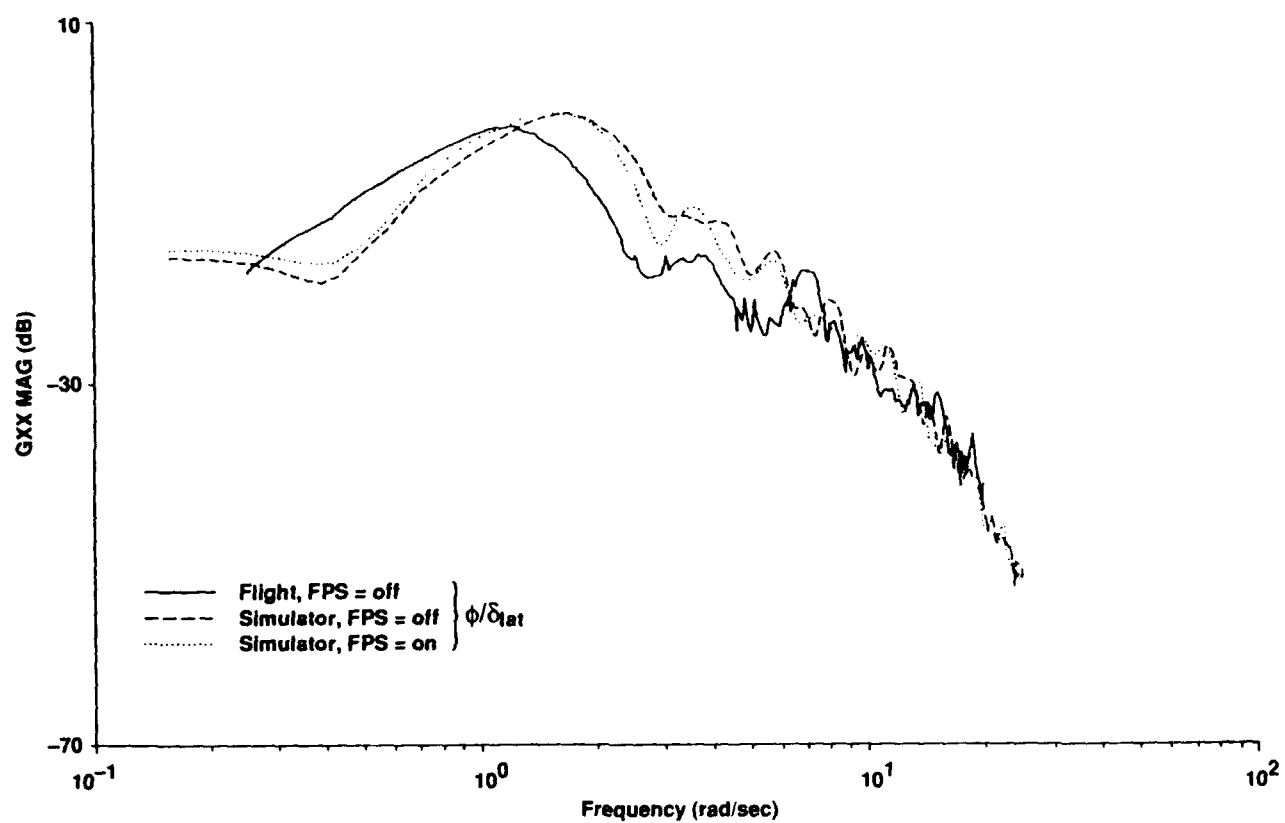
Figure 66. Pilot 2: input power spectra for side-step maneuver, simulator versus flight.
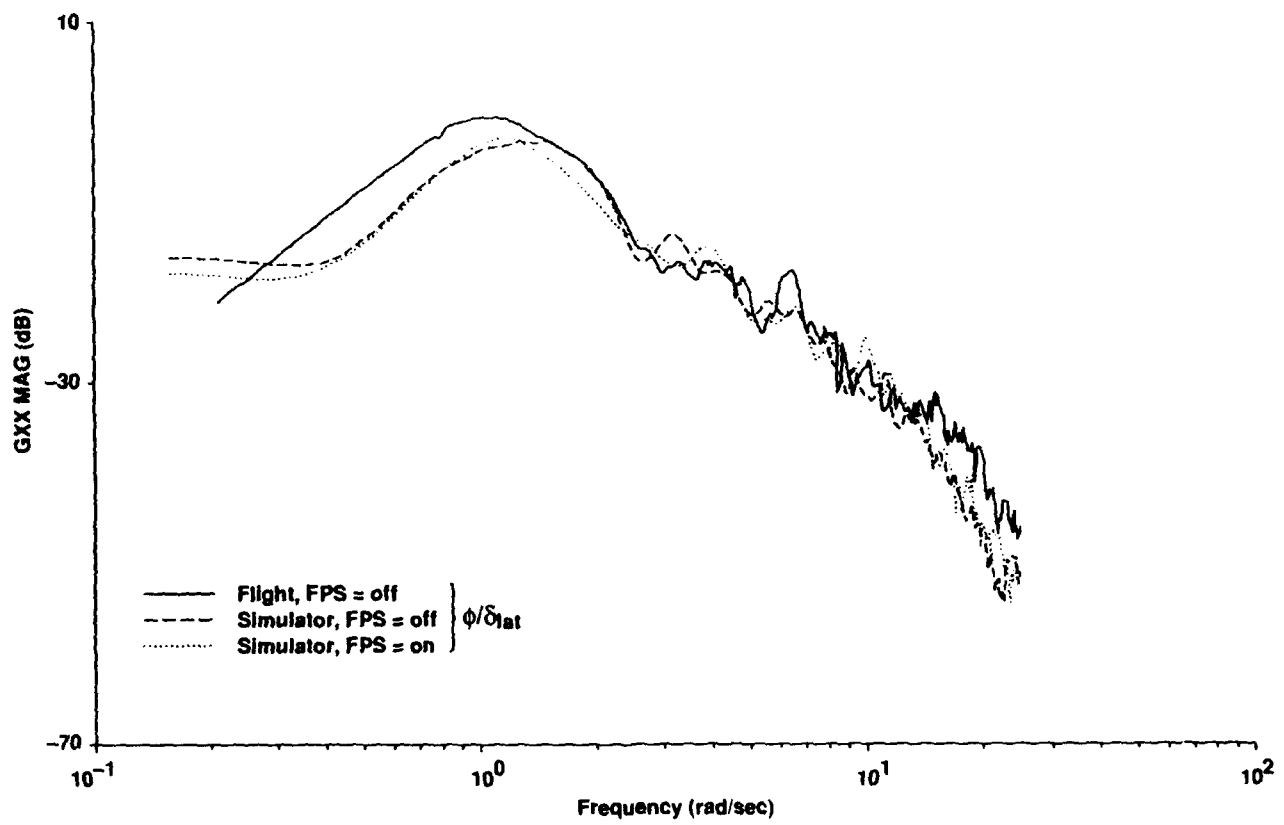
Figure 67. Pilot 4: input power spectra for side-step maneuver, simulator versus flight.
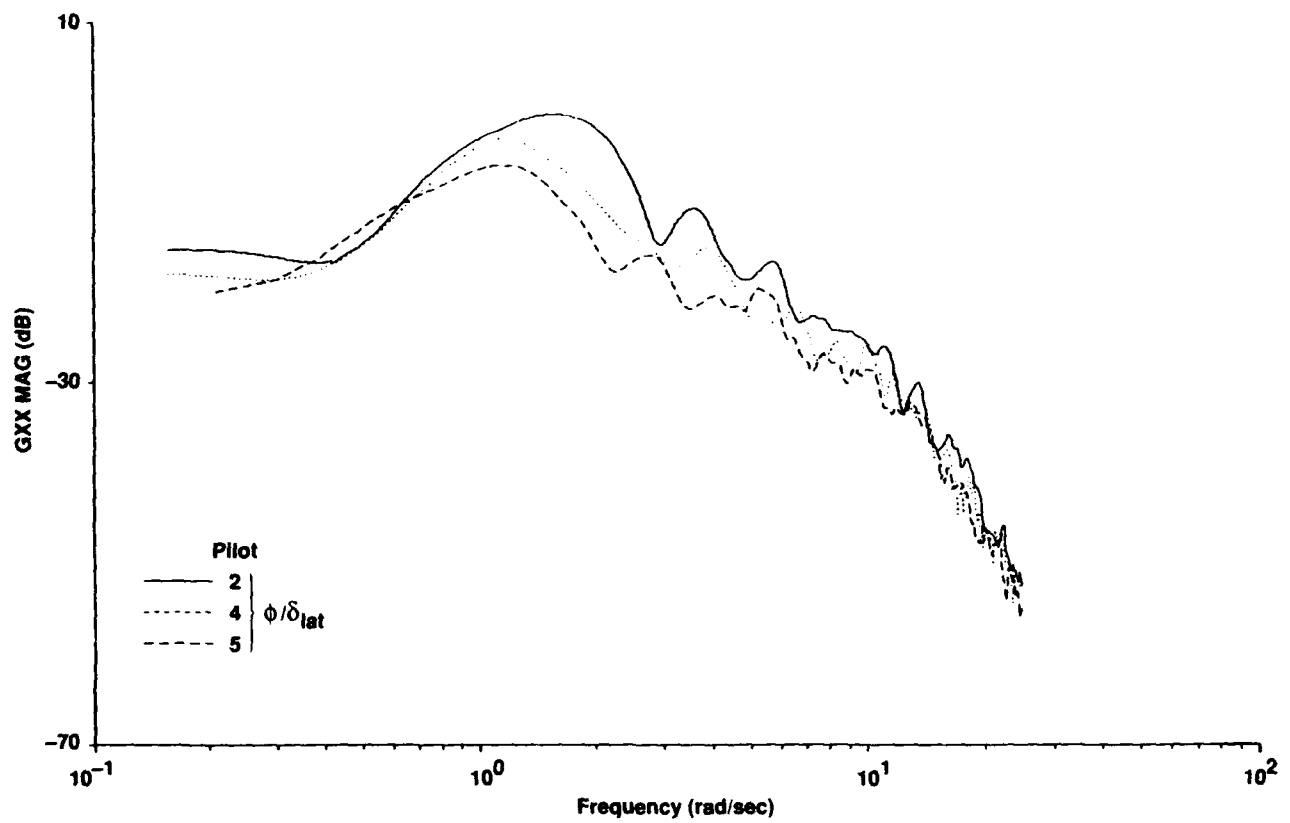
Figure 68. Input power spectra for three pilots in simulator, side-step maneuver, FPS on.
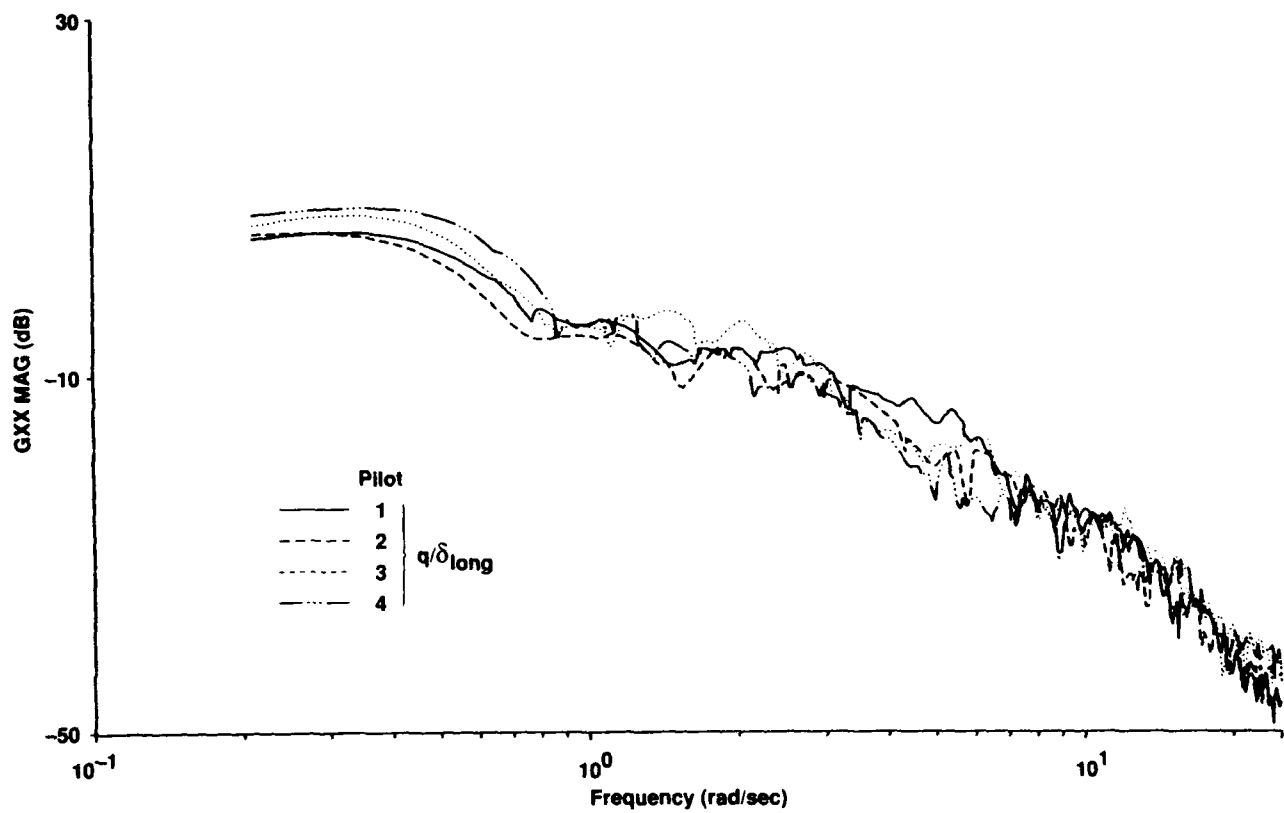
Figure 69. Input power spectra for four pilots in flight test, dash/quick-stop.
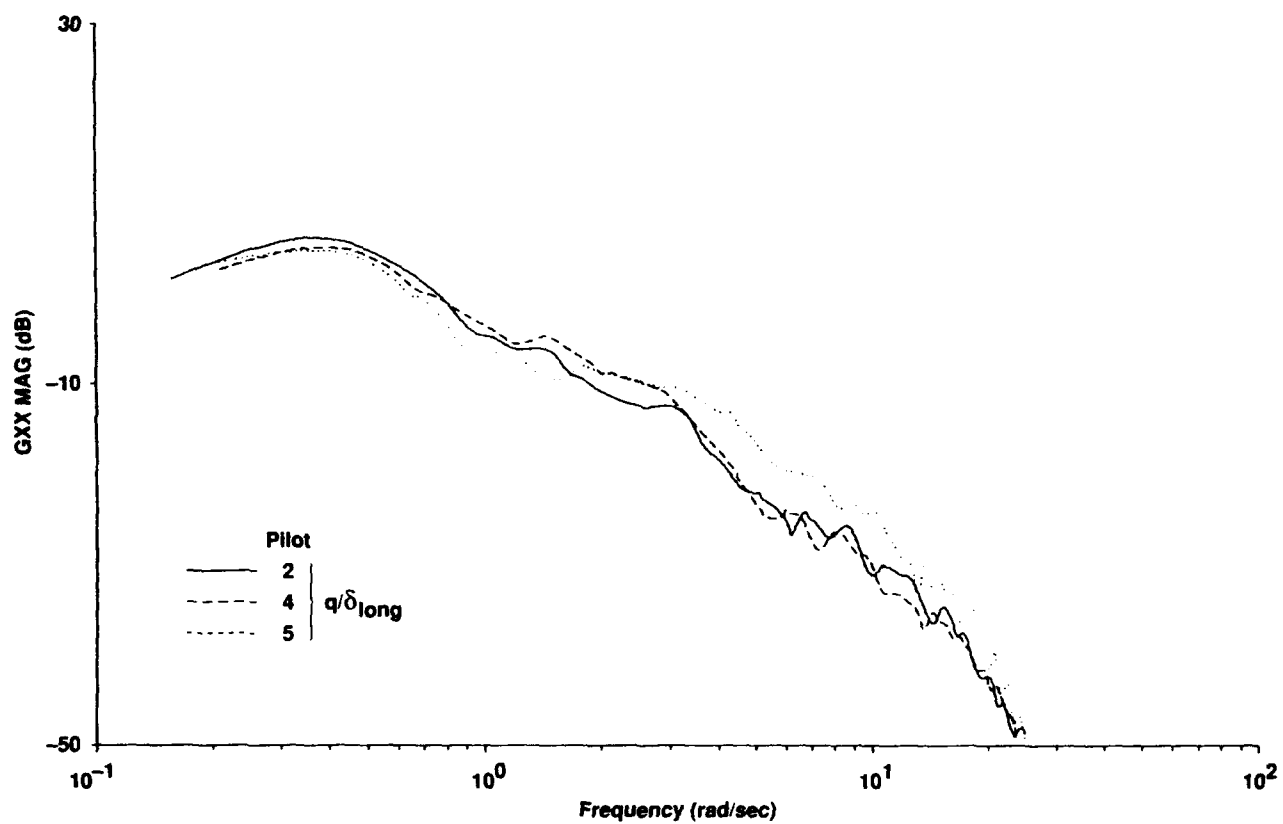
Figure 70. Input power spectra for three pilots in simulator, dash/quick-stop.
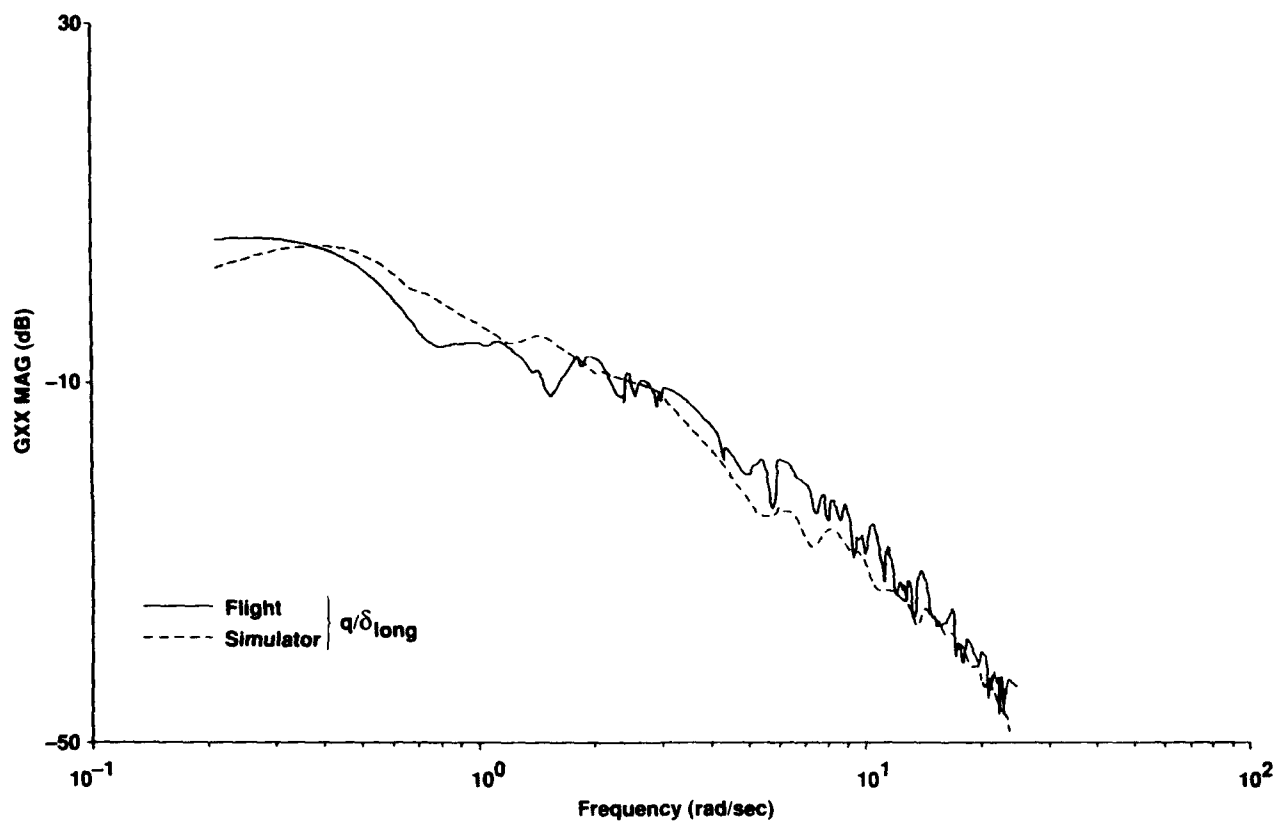
Figure 71. Pilot 2: input power spectra for simulator and flight dash/quick-stop, pitch cyclic.
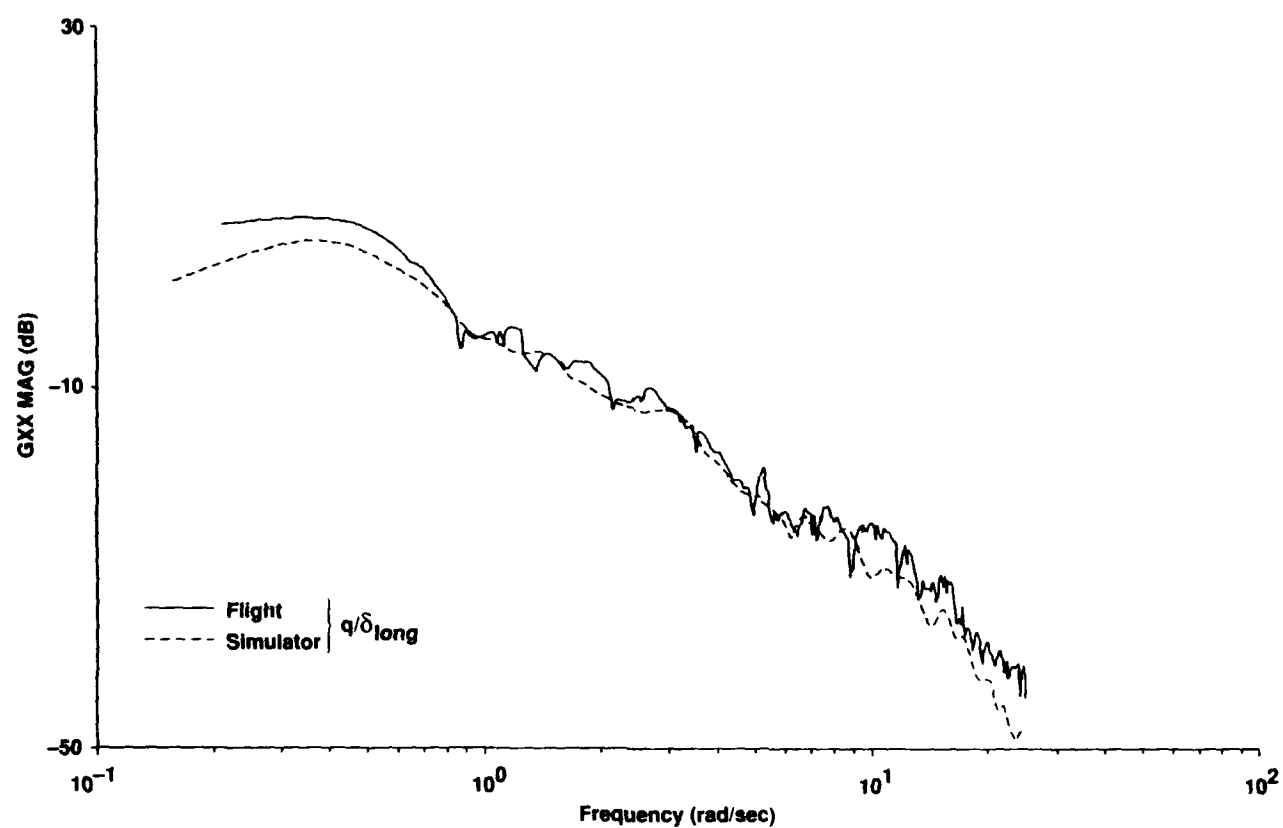
Figure 72. Pilot 4: input power spectra for simulator and flight dash/quick-stop, pitch cyclic.
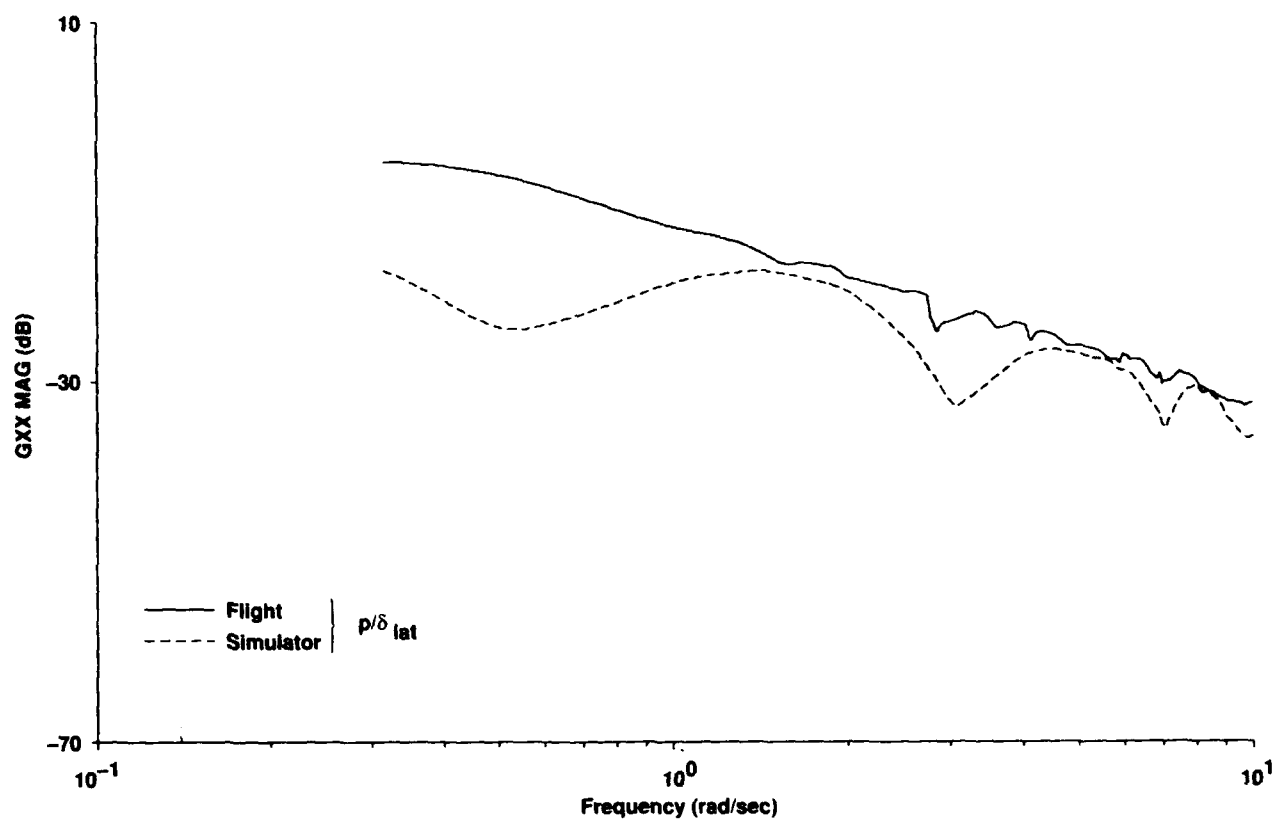
Figure 73. Pilot 4: input power spectra for simulator and flight dash/quick-stop, lateral cyclic.

APPENDIX A

BLACK HAWK HELICOPTER AUTOMATIC FLIGHT CONTROL SYSTEM

The UH-60A Black Hawk helicopter control system is the Automatic Flight Control System (AFCS). The system is described in reference 9 as follows: "The AFCS enhances the stability and handling qualities of the helicopter. It is comprised of four basic subsystems:

1. Stabilator

2. Stability Augmentation System (SAS)

3. Trim Systems

4. Flight Path Stabilization (FPS)

The stabilator system improves flying qualities by positioning the stabilator by means of electromechanical actuator in response to collective, airspeed, pitch rate and lateral acceleration inputs. The stability augmentation system provides short term damping in pitch, roll, and yaw axes. [The] trim/FPS system provides control positioning and force gradient functions as well as basic autopilot functions with FPS engaged."

Additional information on the AFCS can be found in references 8 and 9. The following simplified descriptions of the SAS and FPS and trim are from reference 8. "The SAS functions to provide 3-axis rate damping and lagged rate damping (pseudo attitude retention). The SAS is a dual system with one subsystem (SAS-1) controlled by the analog SAS amplifier and one subsystem controlled by the digital SAS/FPS computer." The SAS is a limited authority system. "The control authority of each (SAS-1 and SAS-2 subsystems) is electrically limited to ±5 percent of total control travel in pitch, roll, and yaw. SAS inputs to the SAS servo valves are additive to provide a total authority of ±10 percent." There is also a turn coordination feature. "At airspeeds above 60 knots indicated airspeed (KIAS), input signals from the No. 1 filtered lateral accelerometer and No. 1 vertical gyro (derived rate) are provided to the SAS-2 system to stabilize yaw during coordinated turns." The FPS is described as follows: "The FPS is primarily an aircraft attitude hold system that incorporates conditional capability for airspeed hold and turn coordination. The FPS works through the roll, pitch, and yaw trim actuator. The FPS can drive the cockpit control to any position to which the pilot/copilot can trim the controls, resulting in a 100 percent FPS parallel control authority. The AFCS limits the rate of FPS within the maximum override force limits (ref. 8)." The FPS attitude hold system is designed to maintain a desired heading or pitch or roll attitude. "The trim attitude once established is automatically maintained unless changed by the pilot. At airspeeds greater than 60 KIAS the pitch axis of the FPS seeks to maintain the airspeed for which the trim attitude has been established." There is also heading hold and turn coordination. "For heading hold (below 60 KIAS), the aircraft is maneuvered to the desired heading with the pilot's feet depressing one or both of the pedal switches. When the pilot or copilot removes his feet from the switches, the aircraft automatically maintains that reference heading." Turn coordination becomes operational above 60 KIAS. "The coordinated turn feature is initiated by by a lateral stick displacement of approximately 1/2 inch and a bank angle of greater than 2 degrees. The feature is disengaged when the bank angle is less than 1 degree and the roll rate has decreased below 2 degrees per second." The trim system is described as follows: "The trim system provides zero force control centering at a pilot/copilot selected trim control position, a spring breakout force plus gradient and a pedal damper force. The trim system is selected by activating the push-on push-off switch, marked TRIM, on the AFCS panel."

The AFCS has been modeled in the Gen Hel mathematical model with full features to emulate the aircraft system as described above. A description of that modeling can be obtained from reference 7.

APPENDIX B

PILOT COMMENTS ON FIDELITY ASSESSMENT TASKS

Bob-Up Maneuver

Flight– Pilot 1, Average HQR = 2: The rotor downwash causes an oscillation of the hover board with about a 4 sec period. Although this is a distraction, I feel that I can maintain position without much compensation. The board makes it very easy, you have real good cueing, especially with the black and white ladder up to the vertical position because when I'm on the lower board I can't see the upper board very well. **Pilot 2, Average HQR = 3**: The one thing I will comment is that the heave control is precise, you have good damping (not like we are doing it in the simulator)—controlled hover height within one to two feet. Heading control? I don't think ever varied more than 2 deg, very precise heading control. The drift—I didn't check it more than twice during the maneuver (spotter was located on ramp for safety reasons and called out forward drift if he felt helicopter was approaching hover board). Previous comments on hover-board target lines—the lines on the outside of the target that are meant to show longitudinal drift are not very effective. You can't tell longitudinal drift until maybe 6 ft or so, the thickness of the line is such that the amount of drift is not detectable. **Pilot 3, Average HQR = 2**: Was using the hover board exclusively. Was surprised to see how easy it was to prevent any significant overshoot and end up at the right hover height in the bob-up and the bob-down. As you get more aggressive, the stabilization to hover on the bob-down takes longer and the overall time for the maneuver remains somewhat the same. We noticed that as we climbed we tended to drift to the right and when we descended we drifted to the left, probably due to collective-to-roll mixing. I don't think longitudinal drift was a problem. I wasn't aware of any longitudinal position change. **Pilot 4, Average HQR = 2**: During the task the airplane does want to go straight up and down, height damping was good. I thought there was no tendency to overshoot. I expected it to be harder than it is.

F-CAB Simulator, July 1989– General Comments (ref. 34): Bob-up was slightly more difficult in the simulator due to (1) poor vertical and horizontal FOV in simulator and lack of ground rush on descent,

(2) image blurring from CGI during ascent and descent, (3) marginal heave motion cues, (4) aural feedback of engine and drive-train noise was poor. Although these difficulties existed, the overall control strategy was the same from aircraft to simulator. **Pilot 1, Average HQR= 3**: The lack of an overhead view makes it marginal for the task—you can't see approach of the limits—would qualify a bit by saying that the aircraft is not much better. The target resolution is better in the aircraft. In the simulator it's a little fuzzy, and picking out the little lines that you are supposed to use to judge distance are very poor (in the simulator). I felt I was drifting, but couldn't pick up cues. I don't think I got outside the performance limits. It was very hard to pick up the longitudinal cues. Seem to have a slight tendency to PIO on arrestment and the aggressiveness is limited by the tendency to PIO. **Pilot 2, Average HQR = 3.5**: Most work is in the heave axis. FOV is marginal—can't see the top hover board until too late. Had to monitor engine torque limit at bottom— very large collective pulls to arrest bob-down. Don't remember them being that large in the aircraft. I didn't get into PIO, but started to get out of phase on both arrestments. Seat vibration seems to help on this task. It helps to mask the simulator noises. Motion cues— subtle, very mild compared to the aircraft. Aircraft is much more seat of pants. In the simulator I seem to float up to board then come back like a yo-yo, that's why I perceive the simulator to have a lack of damping. On the second and third passes, I change my strategy to minimize oscillations, using gained experience from doing the tasks several times. By avoiding the heave problem, I could do the task faster and easier. The heave is just as positive as in the aircraft. **Pilot 3, Average HQR = 3**: Not much different than aircraft except that in the aircraft I guess when the lower board is going to appear and at that time I take a bite of the collective. Then, as it appears, I pull collective to stop. In the simulator I don't have the cues to anticipate such a move. In the aircraft you feel yourself sort of floating up against the top hover board as you approach the stop of the ascent. This cue is missing in the simulator and you end up not compensating enough for the available motion cues. Increasing aggression requires more work in the stabilization of the hover, especially

143

in vertical. **Pilot 4, Average HQR = 4**: On the bob-up maneuver, I'm still wandering around on the pedals. I would really like to think that I could hold the directional better. I'm a little more abrupt with the controls in the simulator than in the aircraft. I find myself doing the task most consciously axis by axis. I'm getting into a drift—sort of an "S" pattern going up and coming down.

N-CAB Simulator, January 1990– Pilot 1: Pilot 1 was not able to complete this task. **Pilot 2, Average HQR = 4**: Axis with most compensation was heave, but have cross coupling with yaw axis. FOV is marginally adequate—need overhead view to anticipate approach to the limit. It's not much worse than the aircraft. The resolution of the targets was better outdoors. In the simulator, it's a little fuzzy and it's hard to pick out the small lines to judge longitudinal drift. Didn't get over-torque. Didn't encounter any problems with limits, but I did get yaw oscillations due to the high-power pull and rotor drooping so yaw compensation was required. There seems to be a slight tendency toward PIO in heave, and it's on the arrestment both going up and coming down. It's hard to describe, I've got some feeling that it's something in the motion combination with the visual that's giving the PIO tendency. In actual flight, the cues are very positive. When you pull collective, you feel an instantaneous g-spike, but in the simulator it's more like a ramp build up in g and it's obviously lighter in here than in the aircraft. I think you get a little better rotor response in the aircraft and no tendency to PIO on arrestment. The aircraft seems a little more stable. The controls feel pretty much like the aircraft. The response in the simulator is a hair sluggish—get a low predictability when you have a high rate built up. No noticeable difference in technique from aircraft to simulator, except I have a tendency (in the simulator) to want to lead the arrestment because of the tendency for PIO. **Pilot 4, Average HQR = 4**: Most compensation from pitch and roll. The collective was getting resolved very quickly. Not a lot of oscillations at the top and less heave overshoots than with the FPS on. The major compensation was the large high-frequency inputs to the pitch and roll to maintain position. FOV is adequate. My attention is focused on the window in front of me. The detail is good. Very slight tendency to get PIO in the collective mode at the top and at the bottom, but less than I saw with the FPS on. I could get the aircraft stabilized more quickly with

FPS off than with FPS on. I didn't want to do the task more aggressively than I did because I'd end up overshooting the arrestment and would take longer to stabilize. Longitudinal position was a problem—much more tendency to drift—it took more attention to hold position. I don't think any difference that I saw in the motion cues between the flight and the simulator was affecting my performance very much. I do tend to fly the simulator more aggressively—I can't say why. I don't think there were real noticeable differences in the response characteristics between the two vehicles (flight and simulator), but I'm willing to admit that I probably fly the airplane less aggressively than the simulator. The noise cues are satisfactory. The force feel system just seems too loose, too light. The airplane stick seems to be more well behaved. **Pilot 5, Average HQR = 4.5**: The first thing I see with FPS off is reduced longitudinal stick force. With the application of collective, as I start to apply cyclic to compensate for collective to longitudinal coupling, the reduced force makes me overshoot and end up putting in too much cyclic—causing me to change my pitch attitude more than I really desired. That gets me working a little bit harder in the pitch axis. The result is that I tend to be less aggressive on collective to avoid the collective-to-longitudinal coupling. I do notice the conscious requirement for about 1/8 in. of directional control with the change in collective setting—up-collective more left pedal, down-collective more right pedal. I don't notice the reduced damping in the other axes as before. I didn't get into a fight with the roll axis. If there was any PIO tendency it was with the collective—a little bit of PIO tendency in long-stick—a couple of adjustments and an overshoot of the correct pitch attitude. I'm just not holding x-position (longitudinal). I drift back. FOV not adequate for seeing longitudinal drift. The absence of view through my feet and the absence of texture doesn't allow me to see the drift.

Side-Step Maneuver

Flight– Pilot 1, Average HQR = 2: Once I attain a roll rate, the hover boards give really good cues. Got a little bit of adverse yaw, have to be concerned about torque when going from board-to-board. The capture of the hover boards is easy although on that one we had a lot of longitudinal drift which I didn't perceive from the boards. Probably drifted 12–15 ft aft. **Pilot 2, Average HQR = 3**: Horizontal setup of boards more stable than the vertical setup. Using hover

144

board with a slight reference to horizon, don't notice that I'm using anything else. Rolled into maneuver at about 14 deg and rolled out at about 22 deg. What limits the aggression? It's probably the short distance between the boards. The time constraint of 7 sec is adequate, anything faster and you start compromising on the arrestment. (Note: The pilot tried several steps, both reducing and increasing board-to-board time. The HQR went down to 2 for increasing the time to 8 sec since the maneuver was fairly mild, and HQR increased to 4 the when time was reduced to 5.5 sec because pilot compensation increased on the roll reversal to stable hover.) I have a tendency to drift in toward the board about 10 ft when I go left to right. I didn't have that same drift when doing bob-ups. The aircraft noise from the engine was a good cue. Slight overshoot in roll on the arrestment, but recovered quickly. No tendency for PIO. Seemed milder from right to left, but all factors were the same otherwise, except didn't get drift forward. **Pilot 3, Average HQR = 3**: Small lateral compensation was required to point you in the right direction. Once you learn to anticipate the roll reversal, there is no problem in roll-control. Aircraft response was quite adequate, sufficiently damped, the rate was sufficient, no PIO. Limits on aggressiveness is amount of roll at start determines how quickly you have to take it out to stop at second board. Only a small correction to maintain hover height. Control of longitudinal position no problem. The distance between the hover boards of only 40 ft means you have to arrest the roll quickly to stop on the second hover board. **Pilot 4, Average HQR = 2**: It's a very good maneuver. It's a precise maneuver mostly because of the information coming off the hover board (you really don't need any other information) It's really sharp with excellent small-angle feedback. The cues for left-to-right are better than for right-to-left. (Note: Pilot was sitting in left seat for this maneuver.) When I go left to right I have the airplane dash board as a reference to bank angle. I think the airplane is well behaved in roll very well damped no tendency to oscillate, feels really solid. Also, I'm really not aware of my control inputs in the airplane I feel that I'm in control of the maneuver. I can stop the airplane almost where I want to. In the simulator yesterday I was cognizant of the control I think about making an input and then taking it out, was really aware of having to think about control input. It's more natural in the airplane. You really can be aggressive and precise in the airplane.

F-CAB Simulator– General Comments: The side-step maneuver was equally difficult in flight and in the simulator primarily because of the limited spacing of the hover boards. However, in the simulator roll damping appeared to be light and the heave cues from motion were marginal. **Pilot 1, Average HQR = 3**: Modified vertical position—a big thing there was roll reversal. One reason I'm not able to get the roll reversal, I'm failing to get the roll reversal timed properly. I'm either late with the maneuver or have insufficient control power in the overall reversal. I go sliding past the board. Hover board height control no problem, a minor amount of collective input to maintain position. Some adverse yaw in roll reversal. The big thing there is you've got to lead it a little bit of directional pedal, so when you bring in the power you are matching it along the way. It's roll reversal that gives me the problem. **Pilot 2, Average HQR = 3**: The FOV is almost better than the aircraft since in the aircraft the doorpost blocks your view. Didn't get into PIO or oscillations. I don't perceive that the roll attitude is the same as the aircraft, in the aircraft the roll attitude I establish on the onset of the maneuver appears to be larger. No different from either direction. **Pilot 3, Average HQR = 3**: I think it's representative of the aircraft. I think that both the aircraft and simulator could benefit from better roll damping. No difference from right to left or from left to right. The visual cues in the simulator with the white pointer on the front of the aircraft may make the pilot concentrate on stabilizing the pointer with a little overwork. This leads to being prone to PIO. The lack of depth perception can lead to confusion on whether yaw is oscillating or whether you have a lateral oscillation, the same is true with pitch versus heave. **Pilot 4, Average HQR = 4**: I'm not able to get a satisfactory hover either at the beginning to initiate the maneuver or at the end of the maneuver after I do the lateral quick stop. I wander around trying to stabilize. The lateral side step itself is not at all that uncomfortable, it's the stabilization at the end to get steady that's bad. I'm working much too hard for satisfactory maneuver. Height control is easy. It's the cyclic manipulation that destroys the stability of the hover. I'm continuously making small inputs to stabilize, causing a high workload. I think I should be doing better than I am, but I can't. I have this vision of how I'm going to do it (thinking of experience in aircraft), but I can't achieve that. I honestly think I'm seeing the bottom of the aircraft (simulator visual) go in the opposite direction of my input and when I try

to correct for that, I get out of phase. Of course, all I have for reference is the nose spike and the windscreen visual. Also, I'd say that the stick is not as well damped as in the aircraft.

N-CAB Simulator, January 1990– Pilot 1: (Note: Pilot 1 had an unusual session due to some problems with simulator setup and his comments are here to illustrate effects from the setup.) Most compensation was in roll with heave a close second. The aircraft is what I call coupled-up (very small damping in roll), there was more activity in roll than in heave. The biggest problem here is the visual. You're sitting there rocking and rolling in the roll axis because the CGI is moving back and forth. It's very difficult to get fine detail in terms of lateral positioning; it's a combination of blurring and elongation. I don't think the CGI is as clear and crisp as it was last July. I wouldn't perceive it as a delay. It has nothing to do with delay because if you're just translating across the board you would be able to perceive it regardless of whether you're going to arrest the lateral translation or not. (Note: Adjustments were made to the CGI after these comments and were constant for the rest of the simulation.) **Pilot 2, Average HQR = 4**: Most compensation in roll axis. There seems to be low roll damping. Again, I think it's probably a time delay and the pilot sinking with the visual. The noise from the motion system gives negative cues. When you get aggressive and then try to arrest the roll out, the motion system noise feeds in and I think you're compelled to give probably a couple oscillations. The FOV is similar to the aircraft. There seemed to be a tendency for PIO in the roll axis during the stabilization time and again that was hampered by the motion system noise and the sense of low roll damping. The limiting factor in aggressiveness was the predictability of arresting the roll. This was not an easy task in the aircraft, but the aircraft is so predictable; when you move the control you get the predicted response. In the simulator, when I think I'm getting a predicted response the motion system cues make it a little more difficult during the stabilization. I get this screaming-speed sensation when I have a stable visual—that has an effect on performance. The controls seem like the aircraft, but the roll forces may be a little light compared to the aircraft. The technique has to be a little less aggressive in the simulator, otherwise I get the extra roll oscillations during stabilization. **Pilot 4, Average HQR = 4**: Definitely complicated task in rudder inputs to maintain heading. Aircraft less

stable in hover—harder to maintain in hover and takes longer to stabilize. I find myself concentrating almost exclusively on the center window. The time to complete the maneuver is definitely the driver that says if I tone down the maneuver I can stabilize within the time required. If I get more aggressive it takes larger inputs to to stop the airplane and takes longer to stabilize. If I didn't disturb the airplane very much, I could stop at the other side within the confines of the task and stabilize. If I tried to do it aggressively, I spent a lot of time settling out the airplane, and that's what ate up my time. I think I was more aggressive in the aircraft (flight test) because you can just put in a bank angle charge it over, and come to a screeching stop. Here, if I put in that bank angle and get it started, I'm going to start taking off right away or I'm going to find myself at a large bank angle at the other end and fighting it. It's the lateral oscillation that comes when stabilizing the large input that eats up the time. I still don't like the stick characteristics, particularly around center; the stick seems to be lighter damped or more oscillations with it than in the aircraft (flight test). **Pilot 5, Average HQR = 3**: Roll rates were predictable again. Achieving the proper roll attitude was predictable. Once again it seemed to take a little more cyclic to get the going back to the left than to the right. A little tendency to PIO in collective. The higher the bank angle during the translation the more the collective PIO tendency in coming back to a stable hover. Still couldn't detect drift away from the hover board. Adequate FOV but lack of texture on ground not good. Even with the little collective application that I would make to settle back into the hover, I could hear the engine and rotor dynamics going on, and it was a good cue to the fact that the power was coming in or going out.

Dash/Quick-Stop Maneuver

Flight– Pilot 1, Average HQR = 3: Realizing simulator limitations, we have tried to design a repeatable maneuver within those limitations. The acceleration is initiated with approximately 15 deg pitch nose down and the quick stop is initiated with approximately 20 deg pitch nose up even though compensation is one of loss of field of view when 20 deg nose up attitude is maintained. Although some view remains from the aircraft, the right side view is partially blocked by instruments, especially the vertical speed indicator, but that's peculiar to this UH-60. The other thing to note is that when you establish the 20 deg nose-up

146

attitude, you bring in collective and the aircraft still wants to go more nose up. I'm having to use forward force on the cyclic to maintain 20 deg nose-up attitude. **Pilot 2, Average HQR = 4**: The FOV limits the pitch up on the quick stop to about 20–25 deg, otherwise you end up losing the ground and all you see is blue sky. With high nose-up attitude, the pilot compensates by looking out the window and closely monitoring the controls. I was barely able to meet the height limit with balloon-up on the stop. Used the corner of the nose as a primary reference and maintained height above ground by cross checks from outside back to cockpit. Used concrete squares on ground as a reference. **Pilot 3, Average HQR = 4**: Holding 20 deg nose down takes considerable effort. I think that is due, in part, to the stabilator scheduling. You have to be on the cyclic to keep from going more nose over. The FOV for 20 deg nose down is adequate, any more than that and you can't see over the dash to the horizon. Got to about 25 deg nose up on stop. Hover boards weren't much help for height reference; I think you get most of the height cueing from your peripheral vision. Looked over right-hand portion of instrument panel to ground. The hover boards might be useful in the later stages of the maneuver to establish hover. Heading easily within 10 deg, wouldn't think that balloon was excessive, no PIO. The maneuver is close to what one might do in an operational setting, you wouldn't want to be much more aggressive because that would be uncomfortable. Limit on aggressiveness is the fact that when you stop and balloon up you have to come back down to the hover height. **Pilot 4, Average HQR = 3**: My performance is not as good as I would like. I tend to slide off to one side as I recover from the quick stop. The FOV is limiting, on the pitch down to start I see only concrete and on the pitch up on deceleration I see blue sky. I tend to rely on my co-pilot for feedback on attitude. I'm not using the crane as primary; I rely more on the ground as it appears to move toward the aircraft as the quick stop is completed. It's a multi-axis task. I'm using cyclic as primary, but use combinations of cyclic and collective to stop. Not a real natural maneuver.

F-CAB Simulator– General Comments: More difficult to perform dash/quick-stop in simulator due to: (1) FOV, lack of texture, and some image blurring during acceleration/deceleration (causing loss of depth perception) in the simulator forced greater reliance on the radar altimeter because of lack of confidence in

height cues, (2) FOV limited initiation of maneuver to −15 deg nose down rather than the 20 deg in the aircraft, and (3) during deceleration a slight jolt of indeterminate axis was felt (later simulation determined that the washout for residual tilt had been set incorrectly). A modification of pilot strategy as a result of experience in the simulator made it possible to perform the maneuver with minimal pilot compensation. However, the strategy relied heavily on the radar altimeter for both height cueing and as a pitch cue eliminating a purely visual dash/quick-stop. **Pilot 1, Average HQR = 4**: I lose important FOV in simulator on the quick stop. In the simulator, I'm having to correct for roll to left or right. Can't remember having to do that in the aircraft. Also, requires significant collective at end of deceleration to establish hover. Very difficult to do this maneuver consistently with the cues that are available. **Pilot 2, Average HQR = 4**: Didn't see any PIO tendency. Maintaining ±10 deg was no problem. Didn't see any problem monitoring engine-rotor limits—only thing that affects how aggressive the task is done is the out the top field-of-view that is in the aircraft but not in the simulator. In the aircraft felt comfortable with 20 deg nose down. Can't do that with any comfort in the simulator. Also, that negative motion cue just as you stop the pitch down is a little uncomfortable. The main thing that limits aggressiveness is the lack of out-the-top FOV. I didn't see any anomalies in control strategy compared to the aircraft—tried to use the cyclic as I did in the aircraft. Work load went up due to frequent cross check into cockpit to check attitude and altitude. **Pilot 3, Average HQR = 3.5**: Motion cueing in heave different than in aircraft. When I upped the level of aggression, I got overly aggressive in the flare at the end of the maneuver and started sliding down rapidly. I pulled hard on collective to stop slide and needed to compensate for yaw—don't remember having to do that in aircraft. In the simulator, I feel that the stick gradient may be too shallow or that the simulated aircraft has low damping. I think this causes a change in pilot strategy in the simulator. **Pilot 4, Average HQR = 3**: Comfortable maneuver, altitude good—felt comfortable to stop at other end. I'm not tending to skull left to right as I did in the aircraft. I did use the radar altimeter for most of the maneuver except for the stop.

N-CAB Simulator, January 1990– Pilot 1: Did not complete this task due to CGI problem. **Pilot 2,**

Average HQR = 4: Axis which required most compensation was the pitch axis. The most compensation initially seems to be in maintaining the pitch because that's a very rapid acceleration and deceleration. In initial pitch there was a tendency to over rotate and had to arrest the rate with stick. The FOV is limited on the acceleration because we don't have through-the-top-of-the-roof FOV that was available in the aircraft although this cab used close to the amount of pitch as in the aircraft. I did get a substantial amount of compensation through the lower window. Scene detail is marginally adequate in that contrast is very low, and the micro texture is very low requiring a lot more attention to pick up on the cues for deceleration, acceleration, and drift. Getting a false motion cue—feel that I am being pulled backwards rather than forward in pitch down. In the aircraft, when you pitch down the aircraft dashes right off. In the simulator, pitch over seems to go back first, then forward—not good. Collective seemed good in this task except was hesitant to pull much collective because of over-rotation problems. Excellent engine noise cues, but not getting strong 4/rev that happens in aircraft. Didn't feel a tendency to PIO. **Pilot 4, Average HQR = 4**: I found myself giving up on the outside scene and coming back into the cockpit and I got much better as I started using the attitude indicator and the radar altimeter for the primary portion of my information. Usually when I got into trouble is when I diverted my attention from three main instruments (the airspeed, the attitude indicator, and the radar altimeter) to make corrections for small directional changes and/or collective changes, usually because I was sinking on the initial acceleration. When I paid attention to any small divergence from flight path I got into trouble in another axis. You really have to work at this and make sure you get everything going in the right direction. The axis with the most compensation is the cyclic followed by collective and minor attention to pedals. With FPS off, the airplane (simulated) has a natural tendency to pitch up as you get to the end because it's thinking that's the level flight where you want to be. I'm having to do it all myself. I'm having to make all the pitch change, hold the nose down, and then bring

it up so it increases my workload by not getting help from the FPS in the pitch channel. I tended to usually over control or under control the pitch. That was my biggest problem. Even with that under control, without vertical information from the scene, I'd find myself with a very high sink rate at the end. Sometimes I under shot by 20 ft and I had to bring it back up. It took me a long time to establish the proper hover altitude at the far end, so second in compensation is the heave response. FOV is not adequate for the task. When you pitch up all you see is sky, when you nose down to accelerate at the beginning, you're skimming across the ground without a feeling for height above the ground. In the aircraft (flight test) I came into the cockpit to finish thing off at the end to make sure that I got right back to the right altitude. I really believe that I did most of the maneuver outside, although what I was really doing was scanning outside to inside with the airplane, and in here (simulator) I'm scanning from inside to outside. **Pilot 5, Average HQR = 6**: Only way to adjust pitch attitude is with attitude indicator. Can't see out top of simulator as can in aircraft, so have no FOV. Because of having to come inside you over shoot the pitch attitude. Needed a lot of compensation by going from inside to out. Had continuous adjustment of collective to maintain altitude. Acceleration cues do not feel true. Feel pitch, but as I get attitude adjusted, instead of feeling acceleration at pitched attitude, I feel that I'm in a dragster—feel like x-axis only no nose down and rotation. On stop, the nose comes up and only the sky is in view. Poor cues in visual to detect yaw—can't see yaw cues at all. Still resulted in predictable balloon—push collective down, get engine/rotor noise, add power to keep from settling, get red lights on and rotor droop. When aircraft starts to slow to 35 knots, used about 1.5 in. collective, 1 in. cyclic, settling sensation pretty good. Weird motion cue during flare to deceleration. Feel light in head as though reducing g force. Not sure if it happens in aircraft—it shouldn't. Motion response doesn't seem real. Absence of texture makes it difficult to recapture hover without three or four over shoots.

APPENDIX C

TIME HISTORY DATA
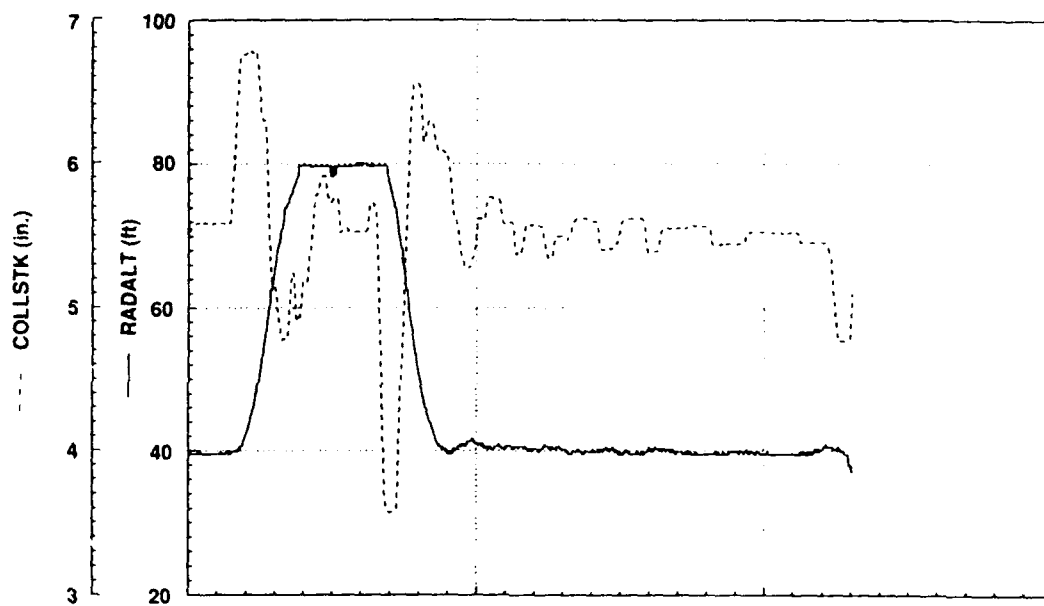
Figure C-1. Bob-up time history data for flight (Pilot 1).
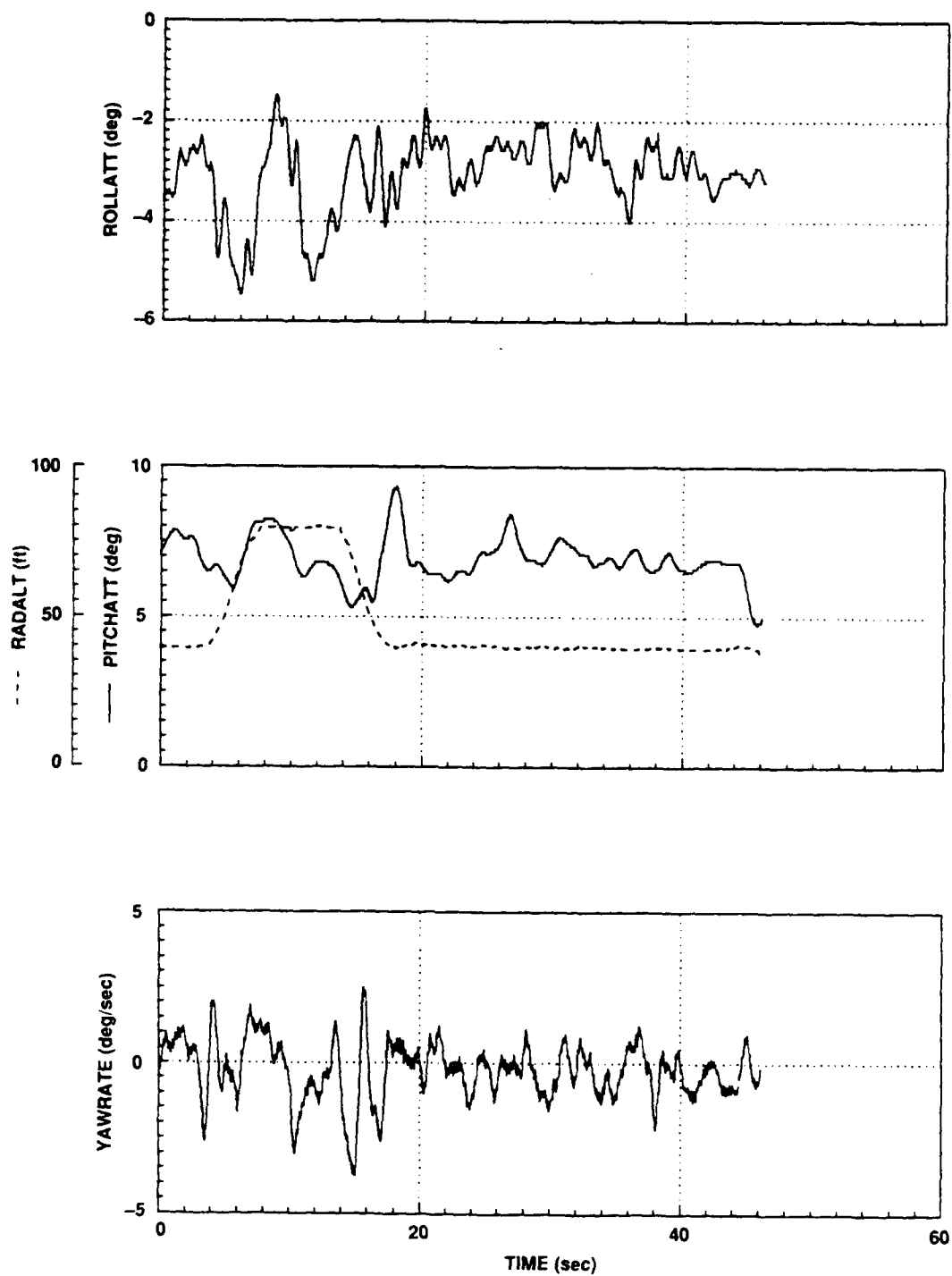
Figure C-1. Bob-up time history data for flight (Pilot 1) (Continued).
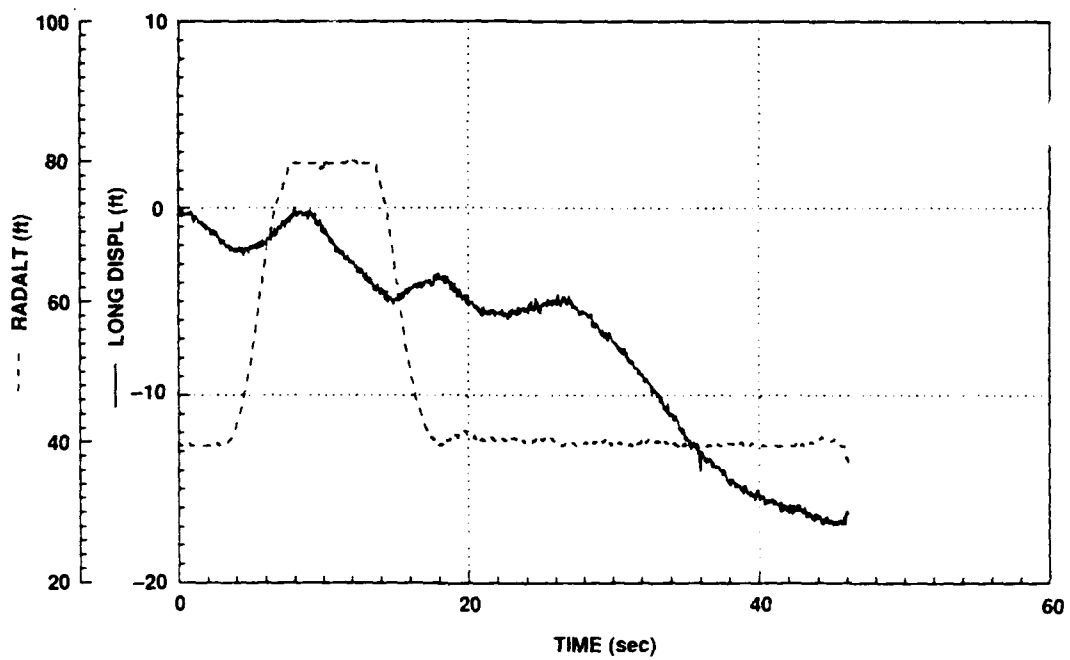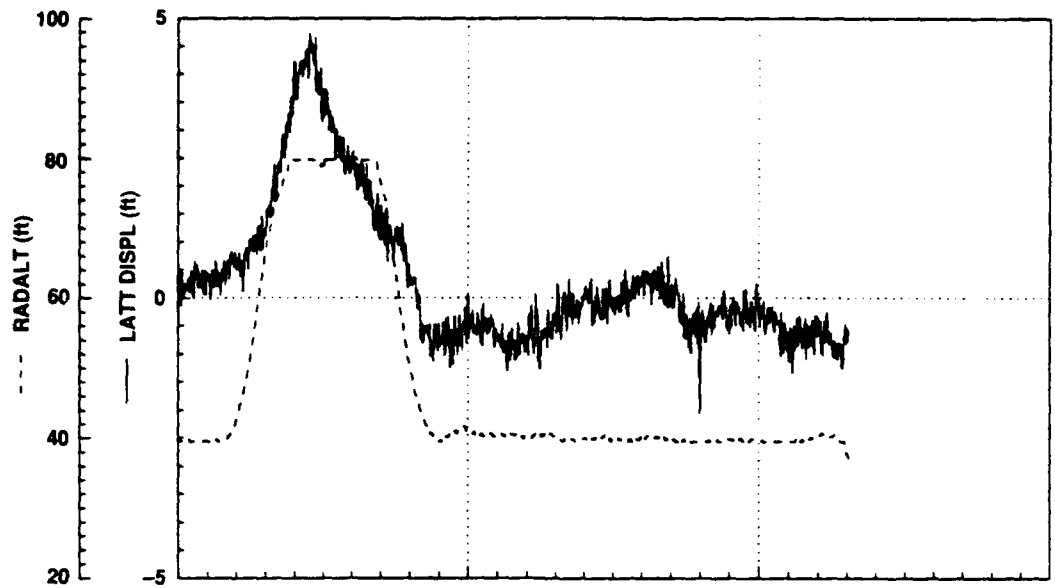
150

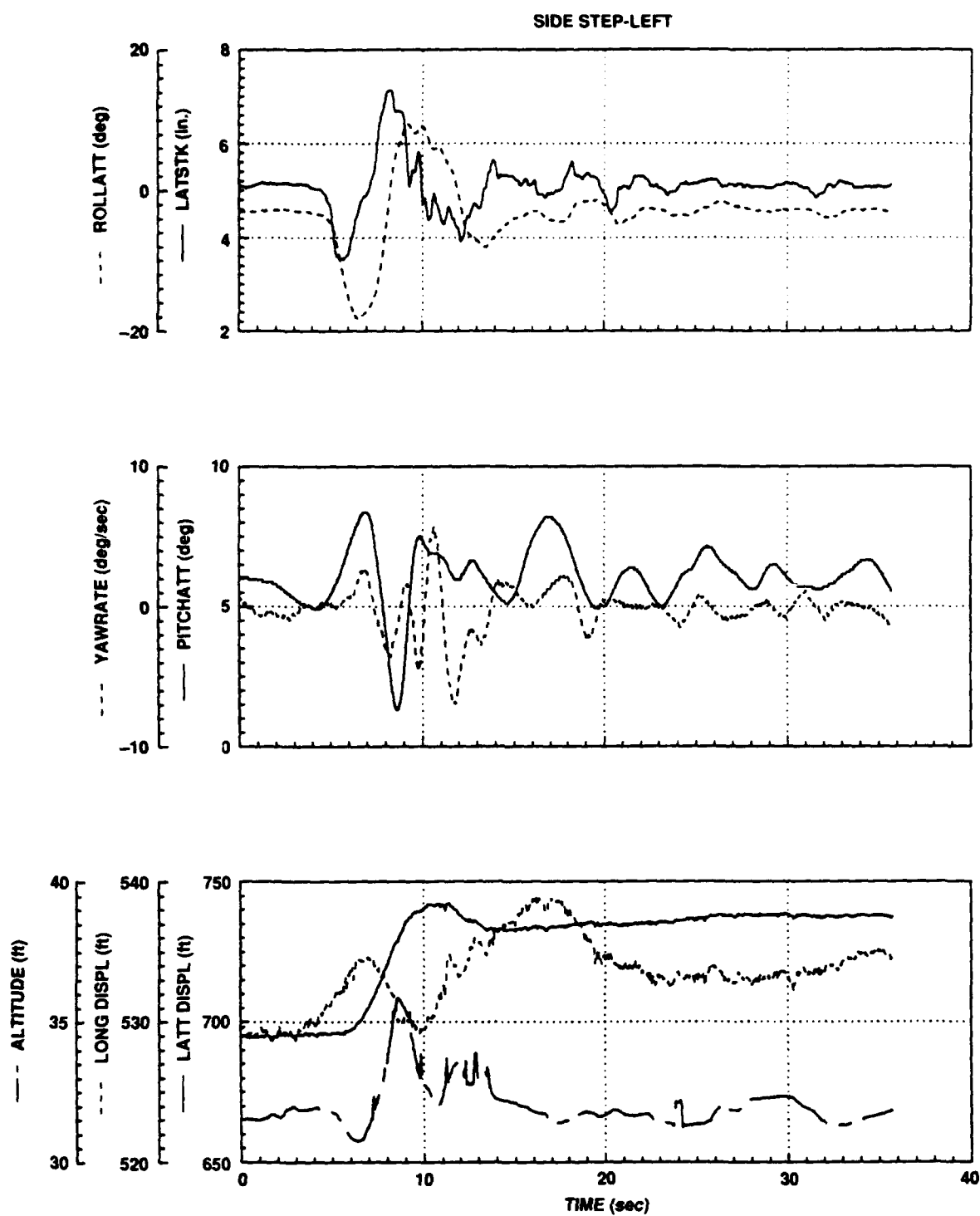Figure C-1. Bob-up time history data for flight (Pilot 1) (Continued).

Figure C-1. Bob-up time history data for flight (Pilot 1) (Continued).

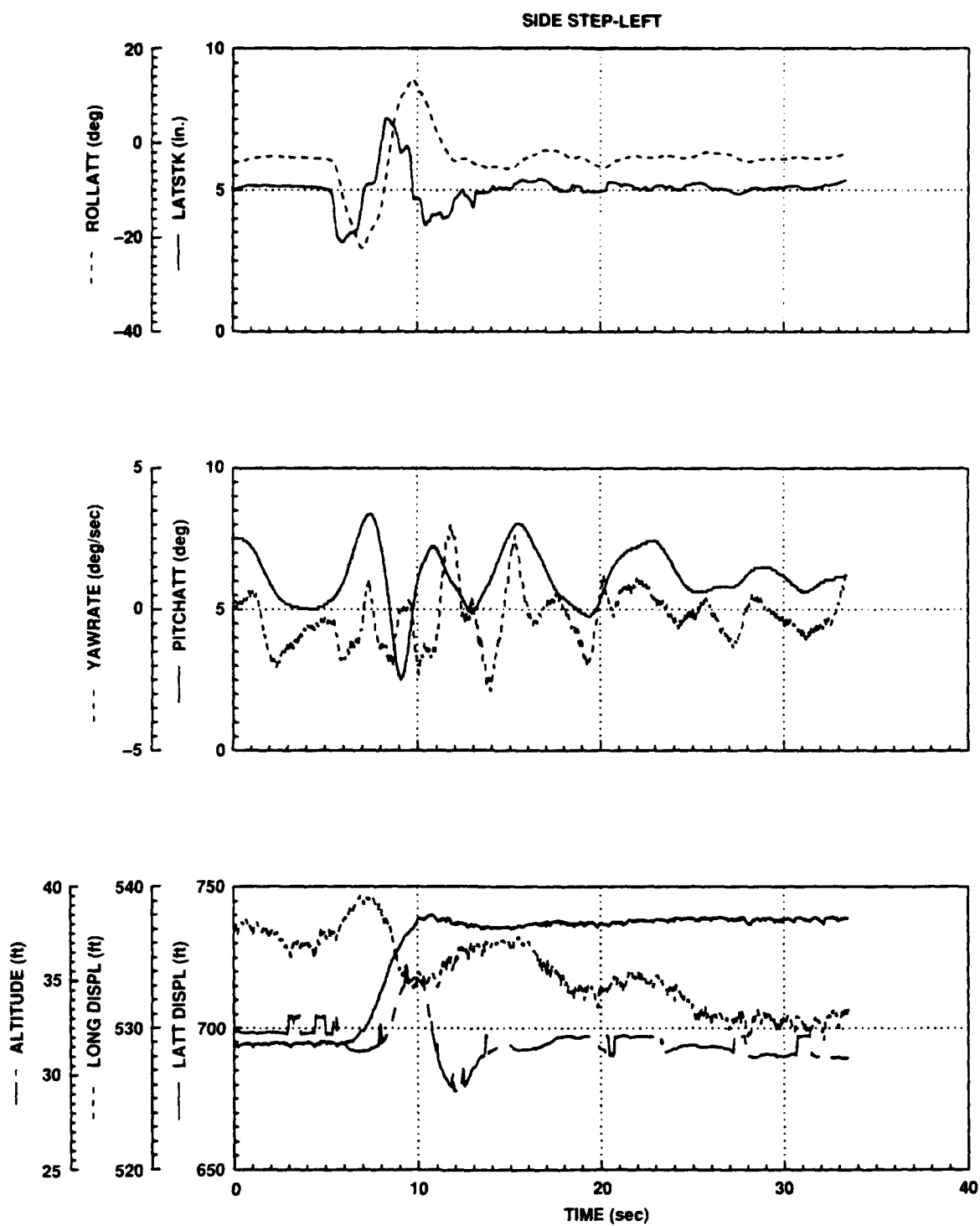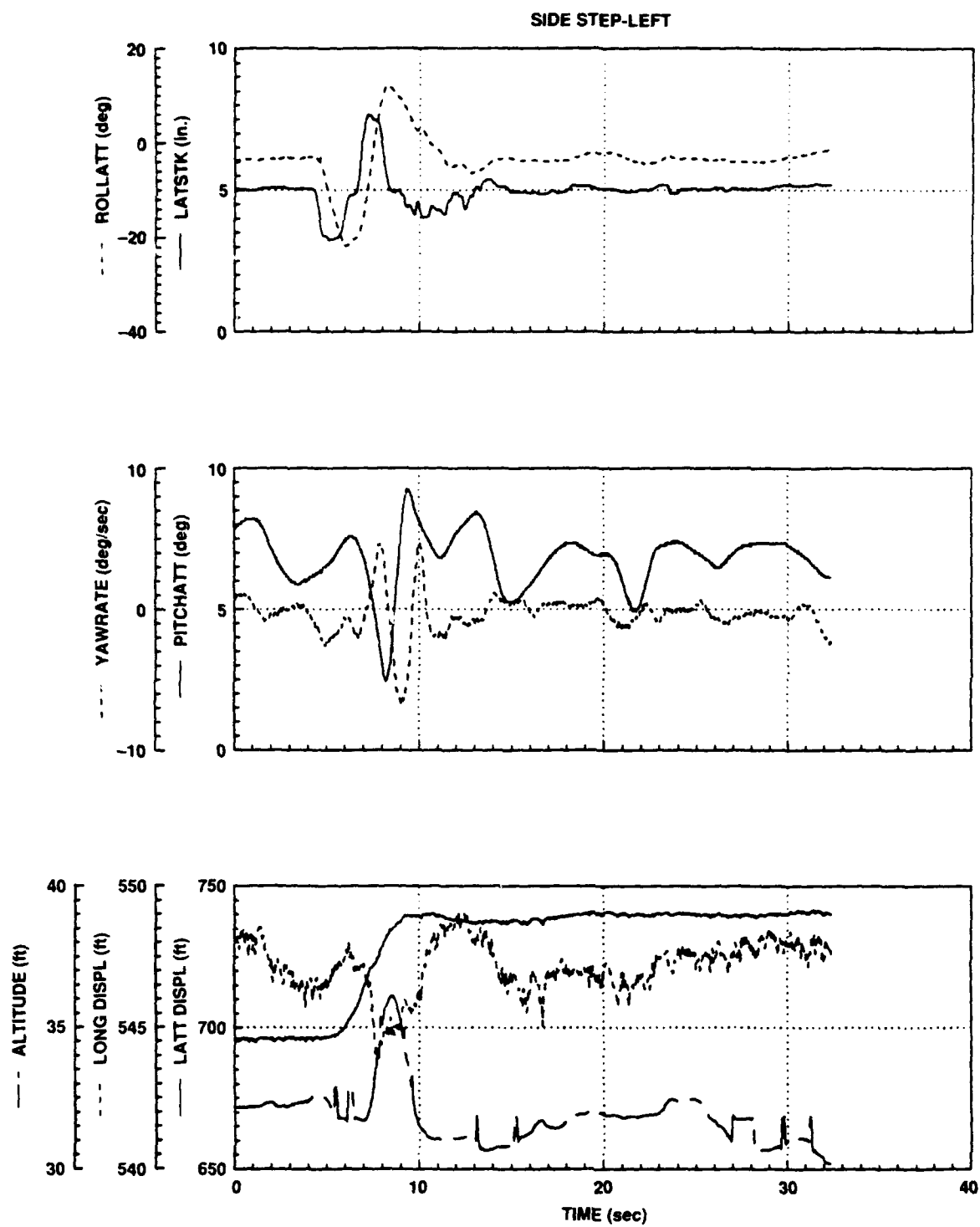Figure C-1. Bob-up time history data for flight (Pilot 1) (Continued).

153
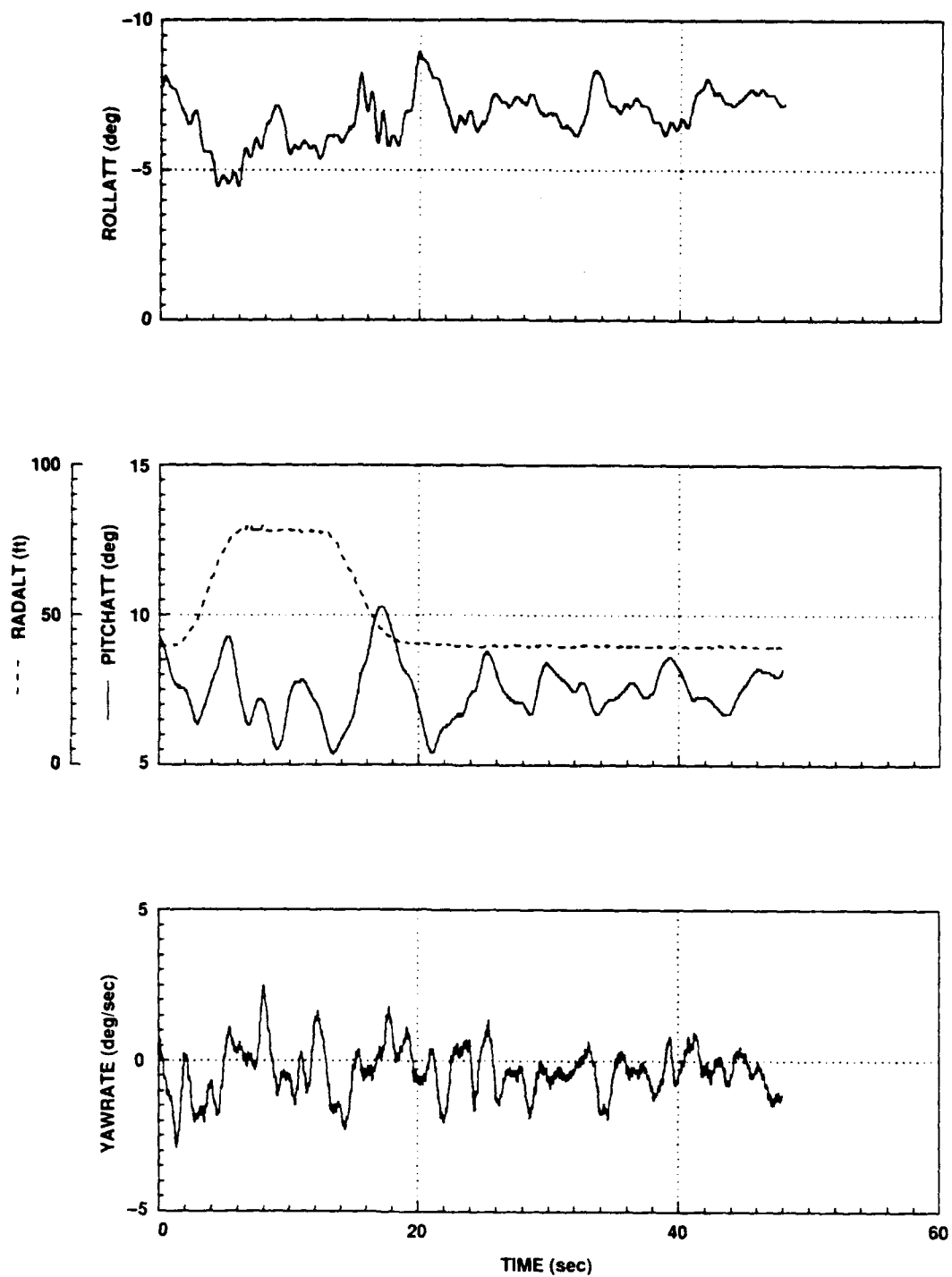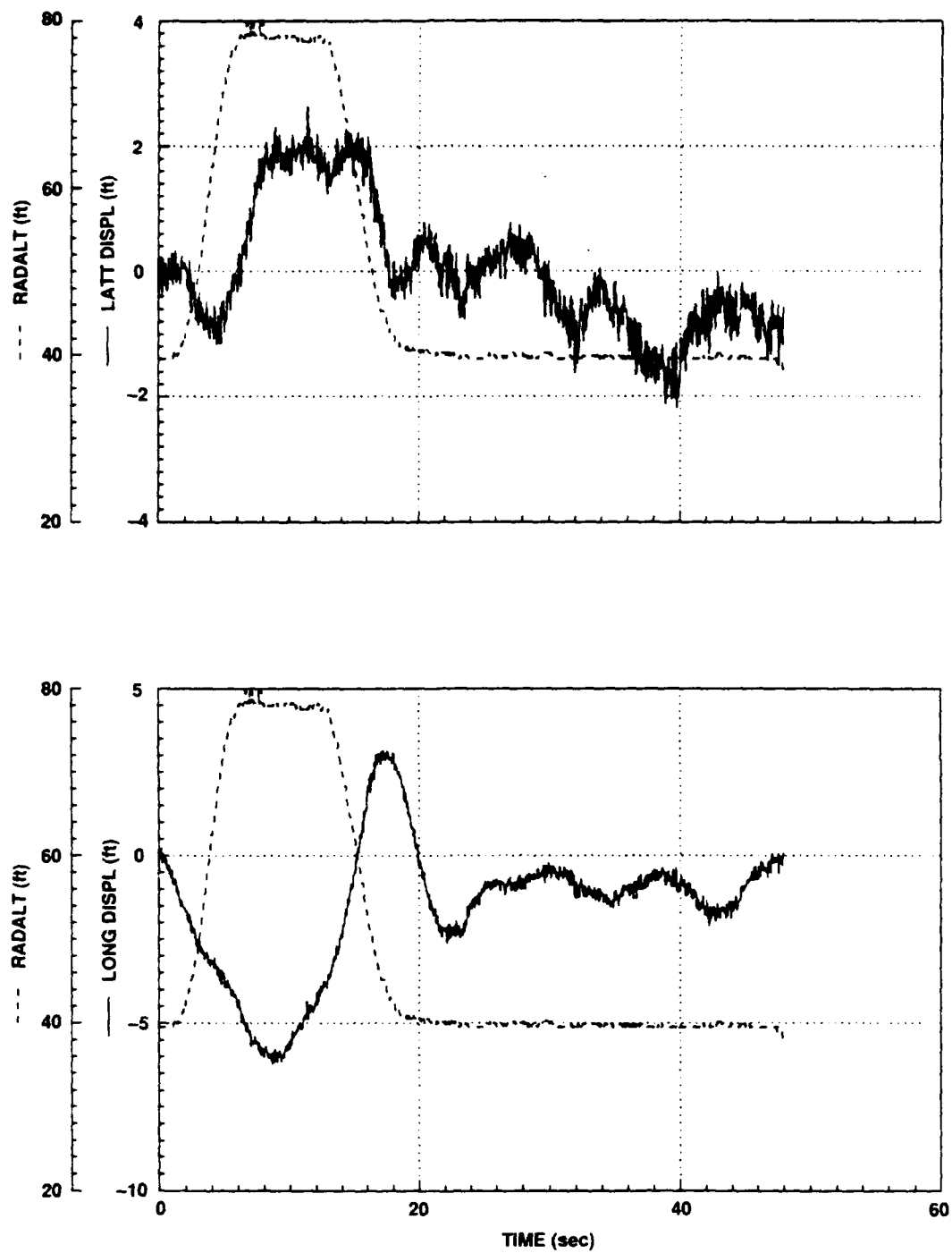
Figure C-1. Bob-up time history data for flight (Pilot 1) (Continued).
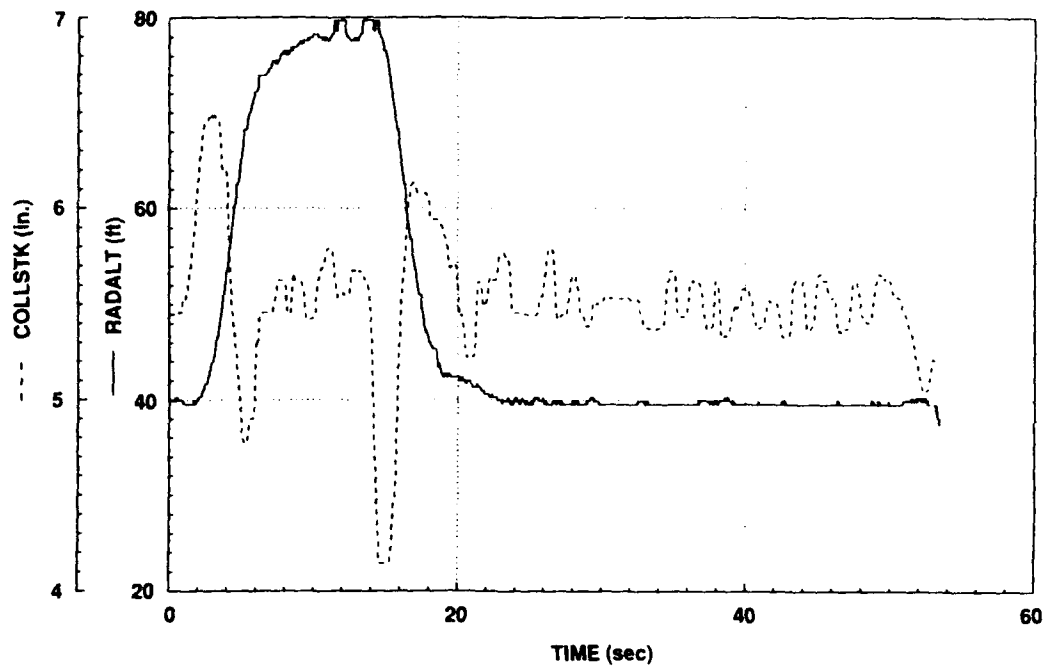
Figure C-1. Bob-up time history data for flight (Pilot 1) (Continued).
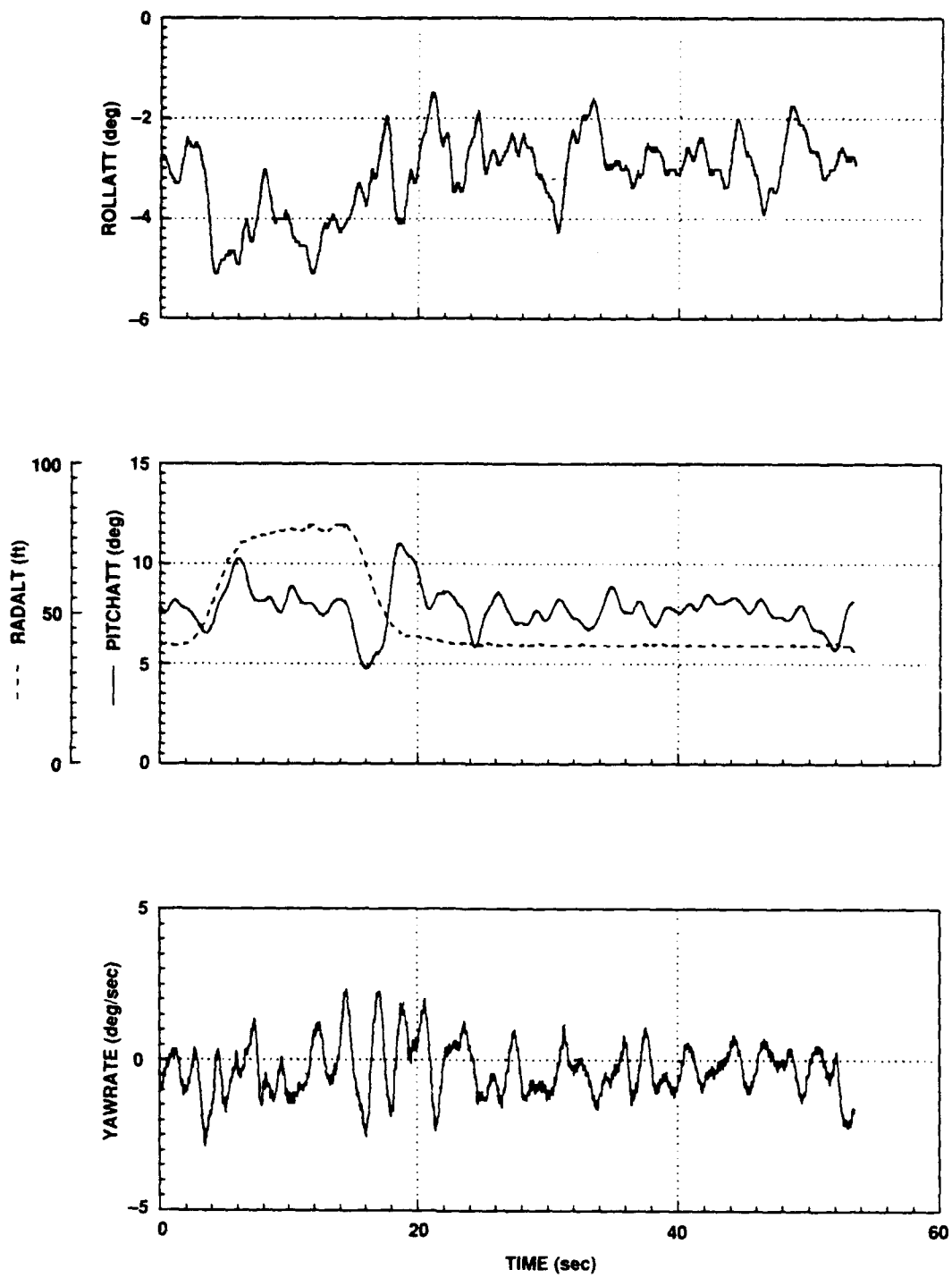
Figure C-1. Bob-up time history data for flight (Pilot 1) (Continued).
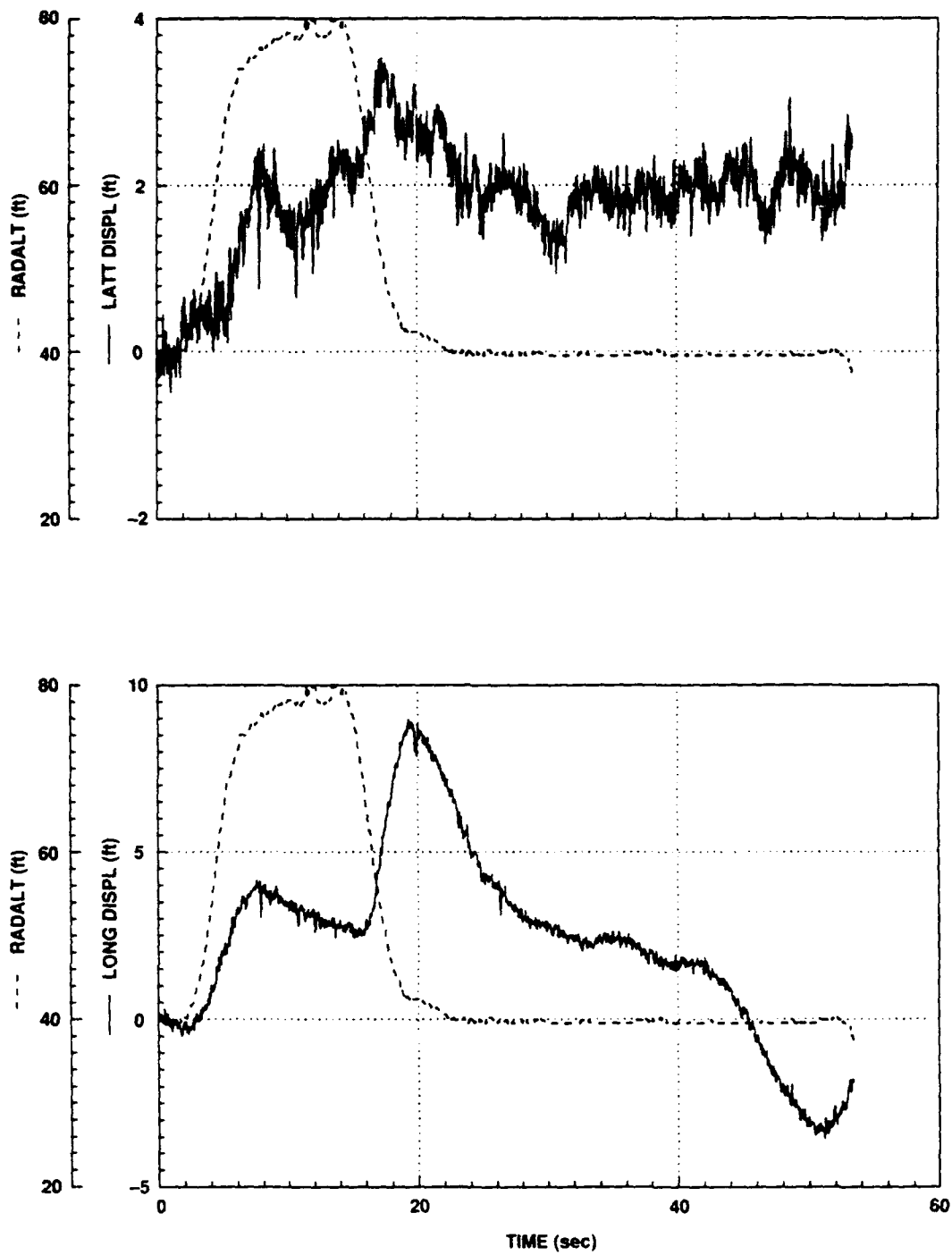
Figure C-1. Bob-up time history data for flight (Pilot 1) (Concluded).
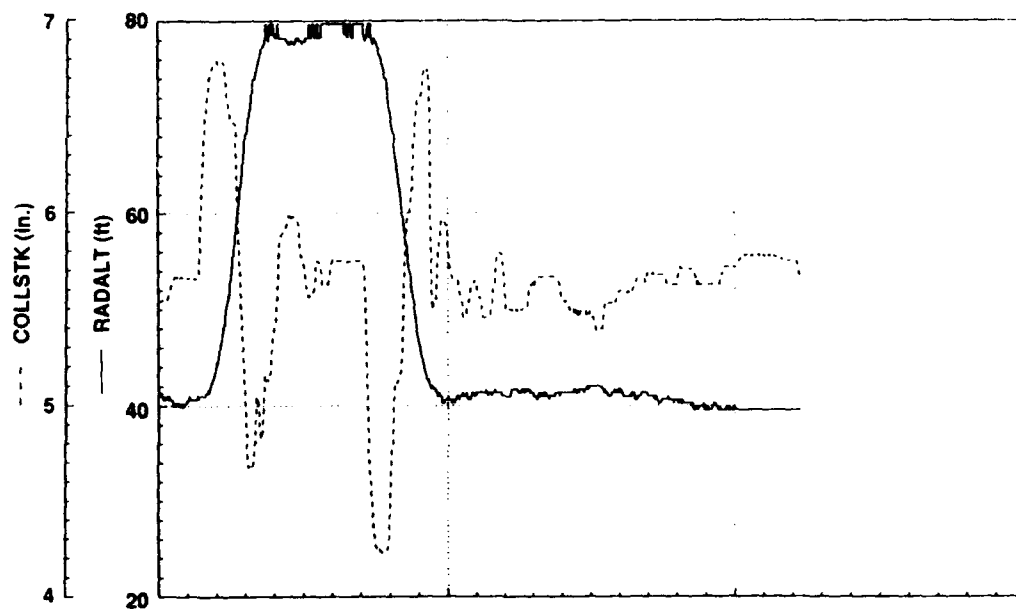
Figure C-2. Bob-up time history data for flight (Pilot 2).
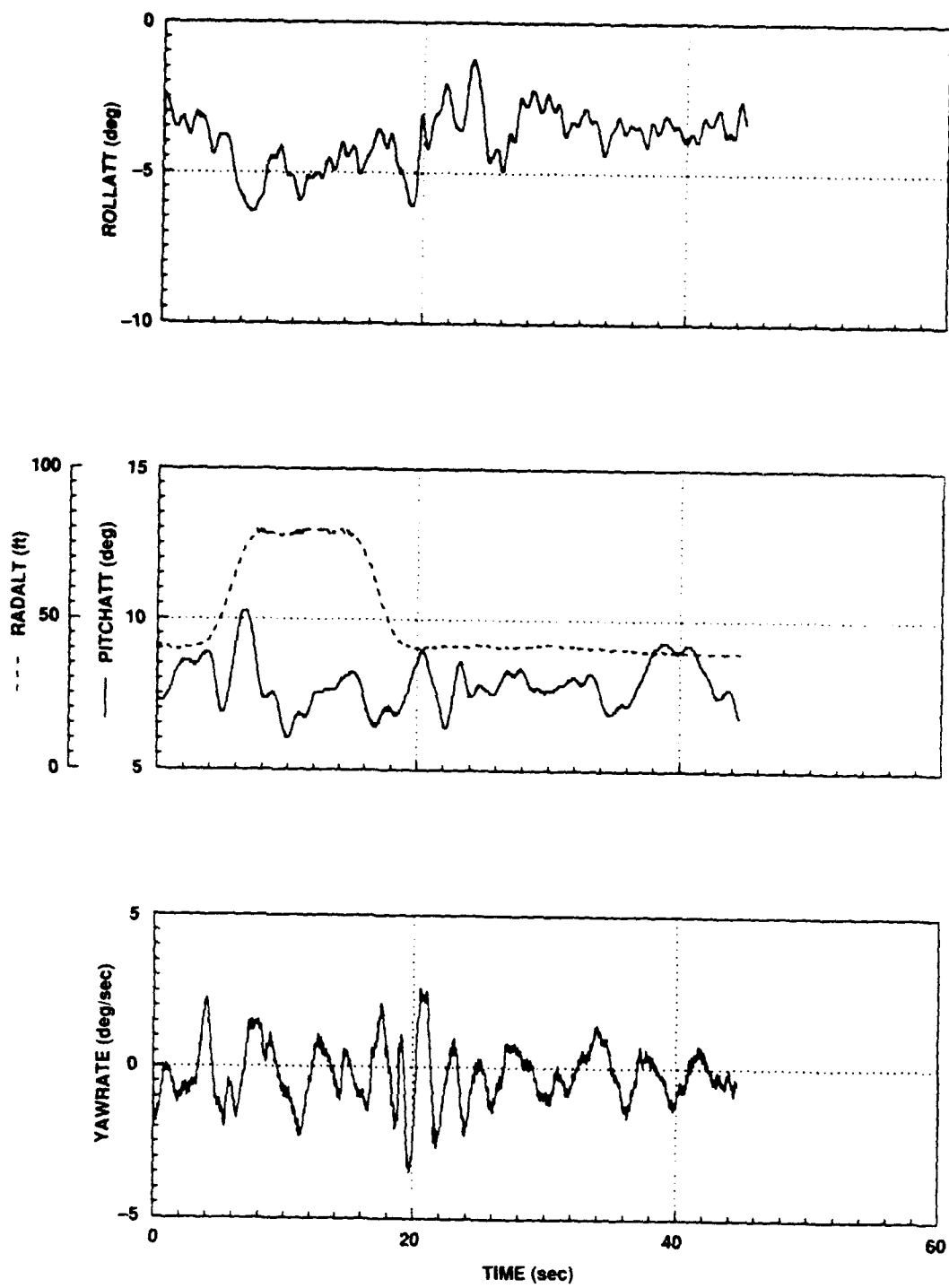
Figure C-2. Bob-up time history data for flight (Pilot 2) (Continued).
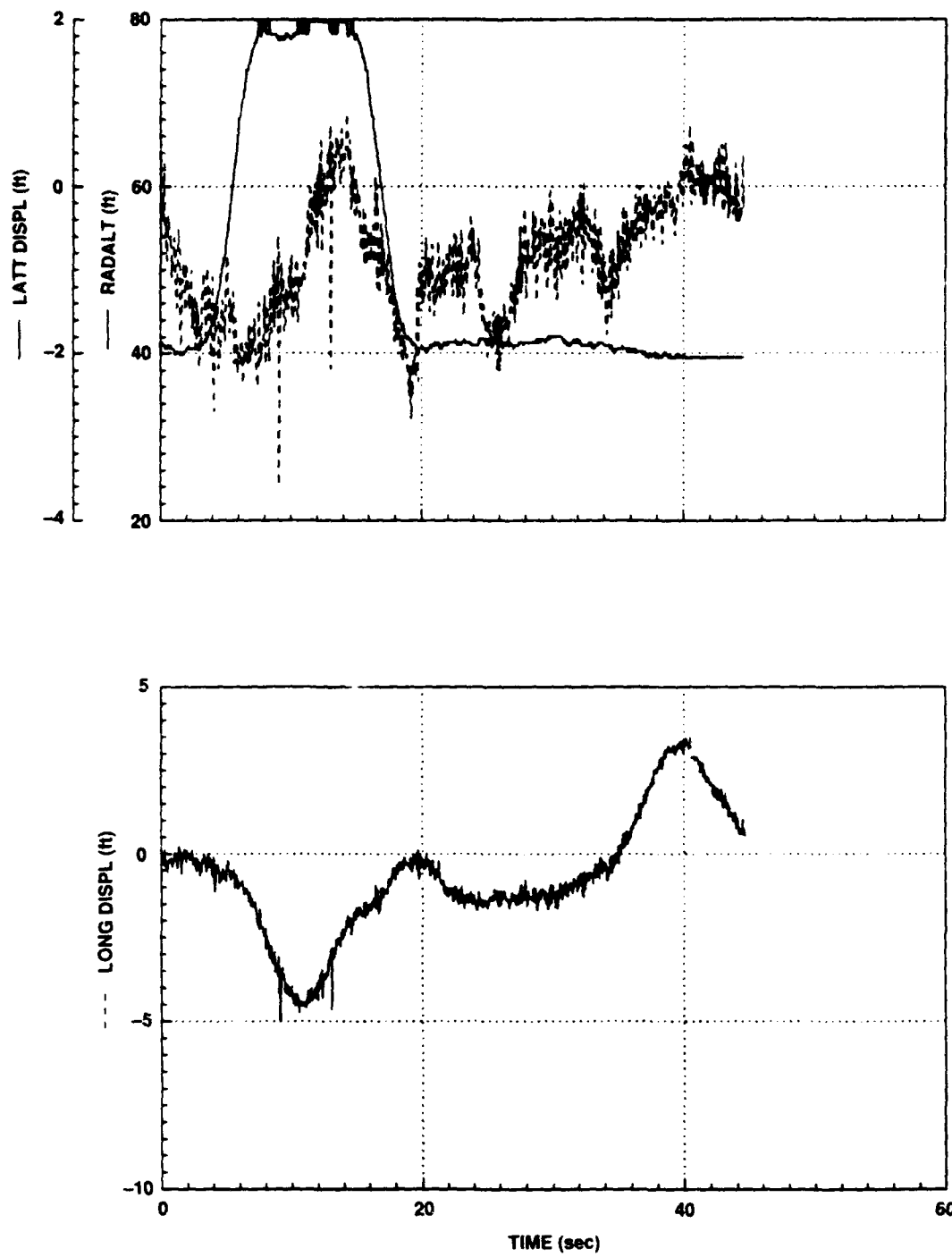
Figure C-2. Bob-up time history data for flight (Pilot 2) (Continued).

Figure C-2. Bob-up time history data for flight (Pilot 2) (Continued).

Figure C-2. Bob-up time history data for flight (Pilot 2) (Continued).

162
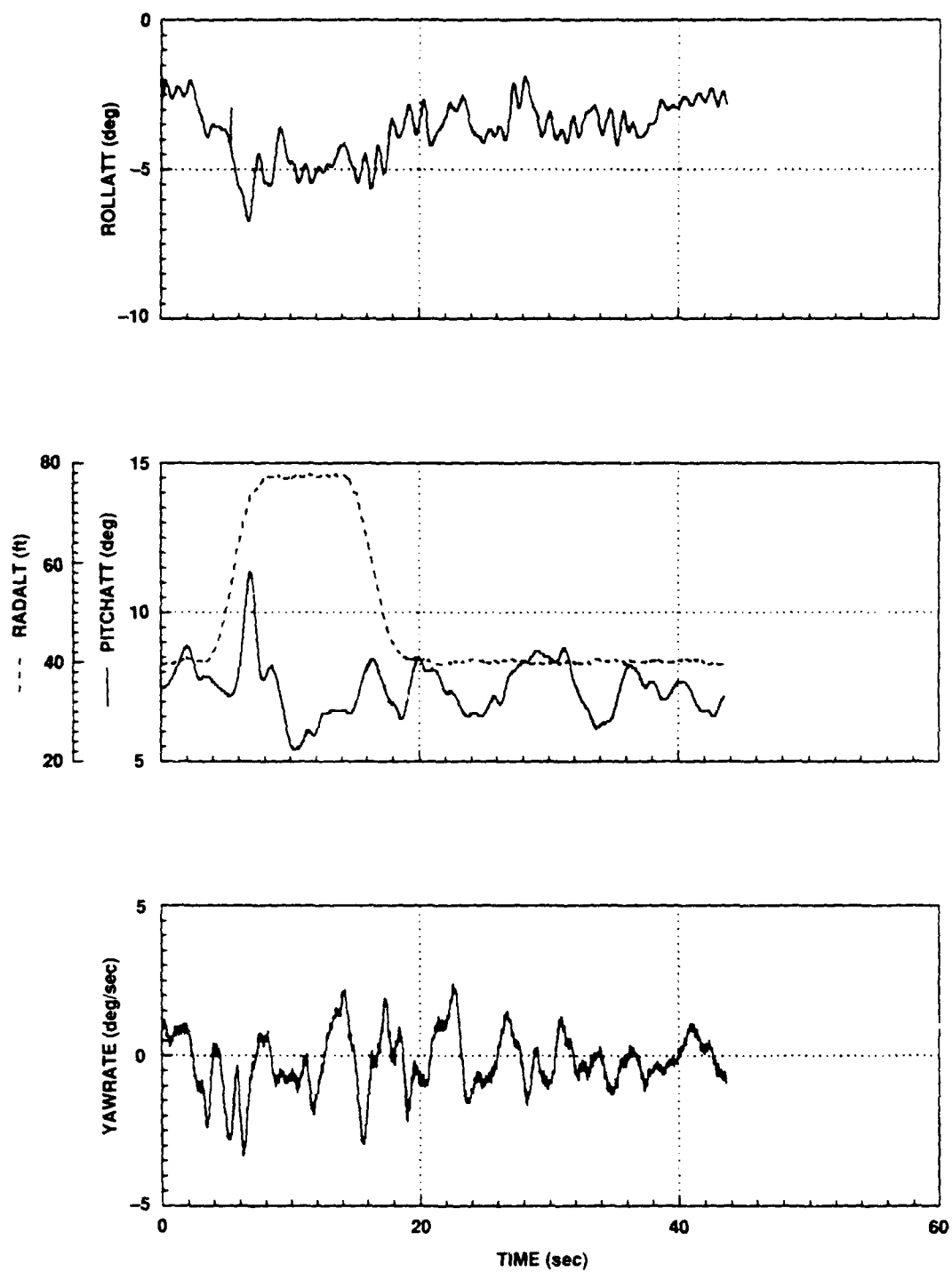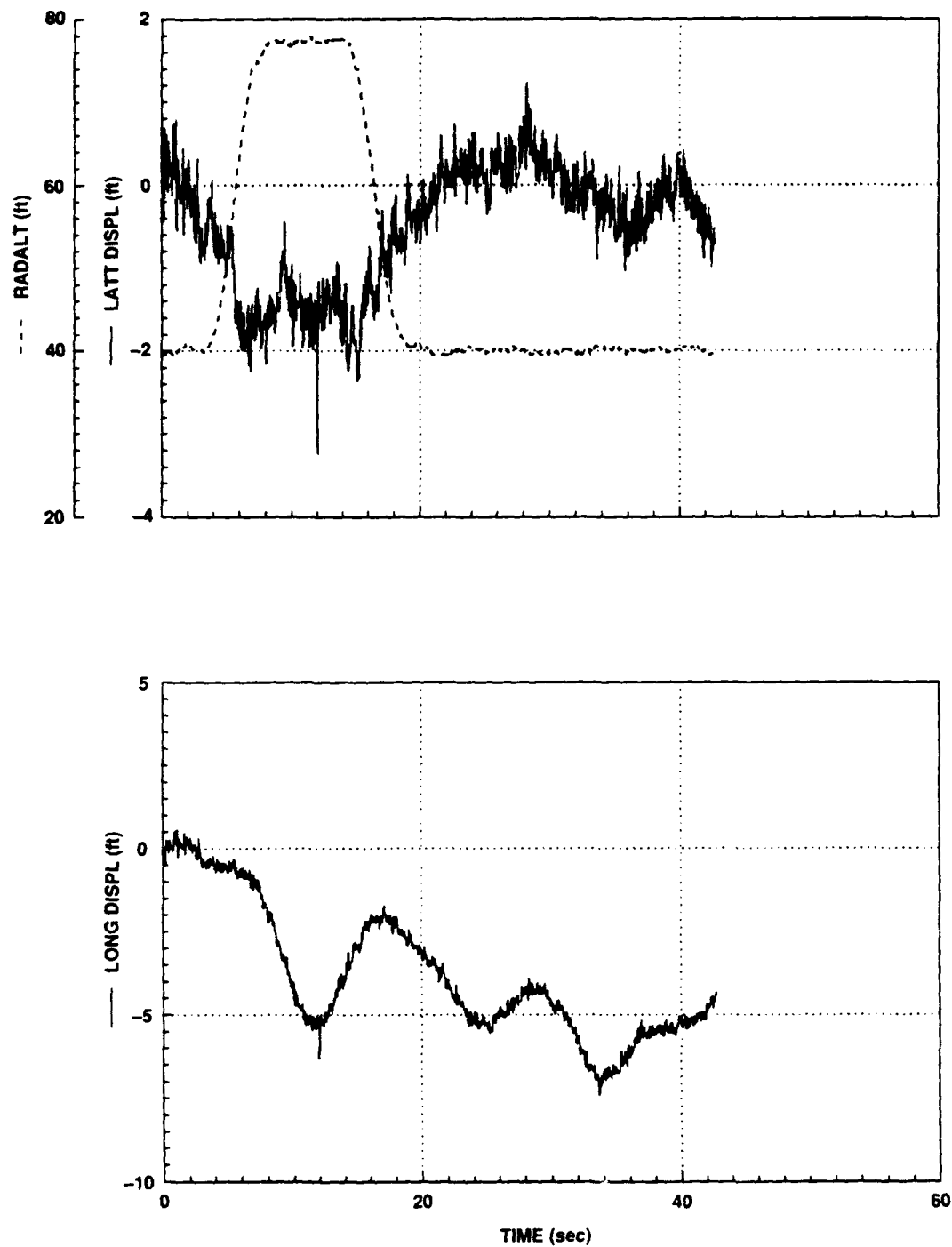
Figure C-2. Bob-up time history data for flight (Pilot 2) (Continued).
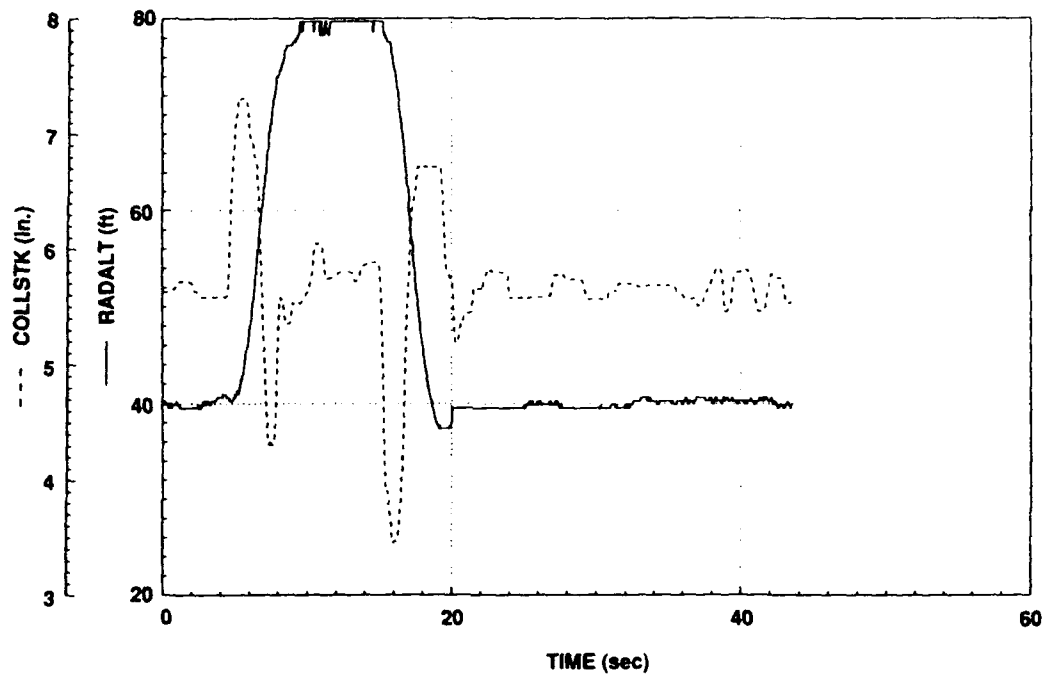
Figure C-2. Bob-up time history data for flight (Pilot 2) (Continued).
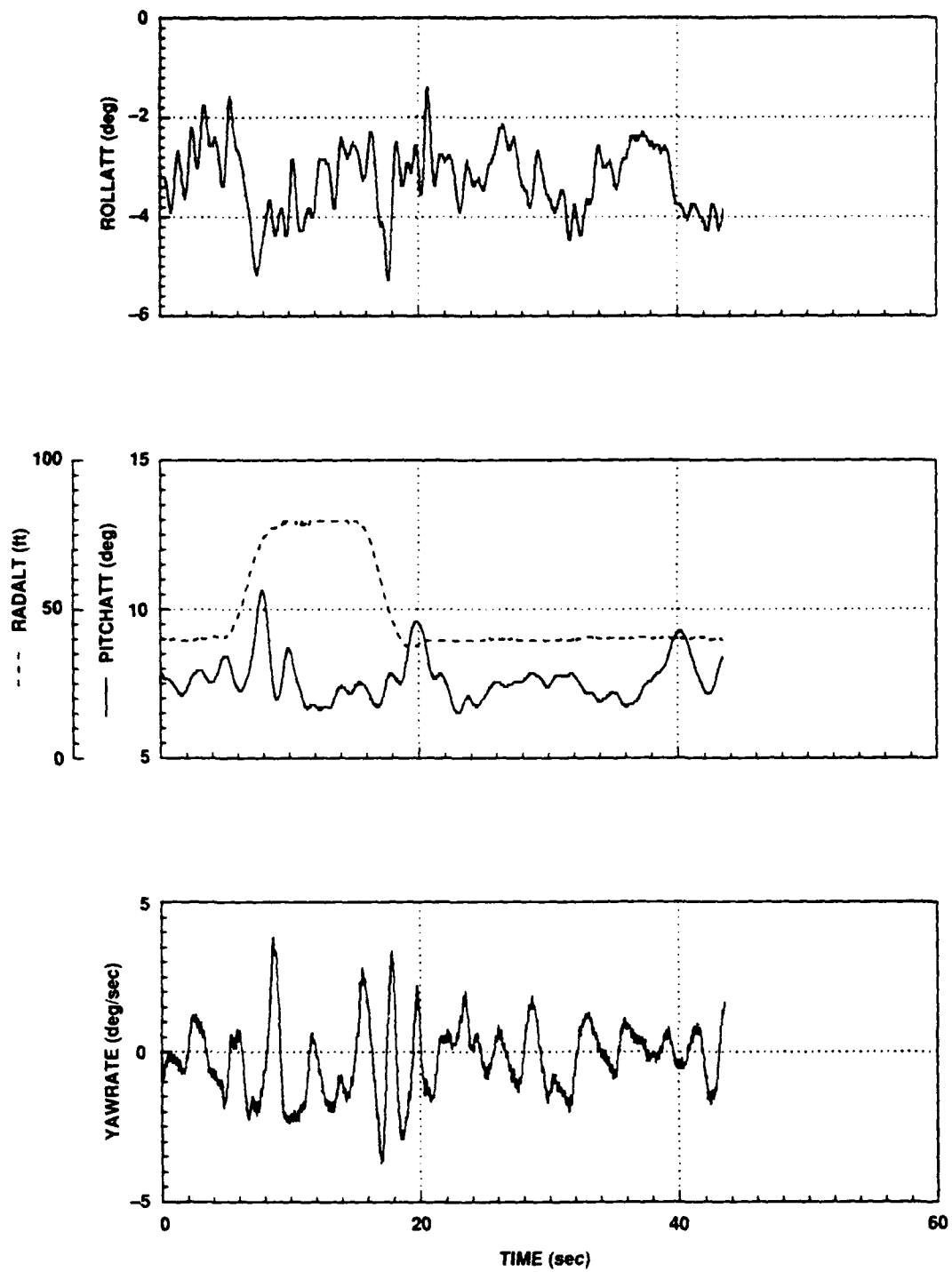
Figure C-2. Bob-up time history data for flight (Pilot 2) (Continued).
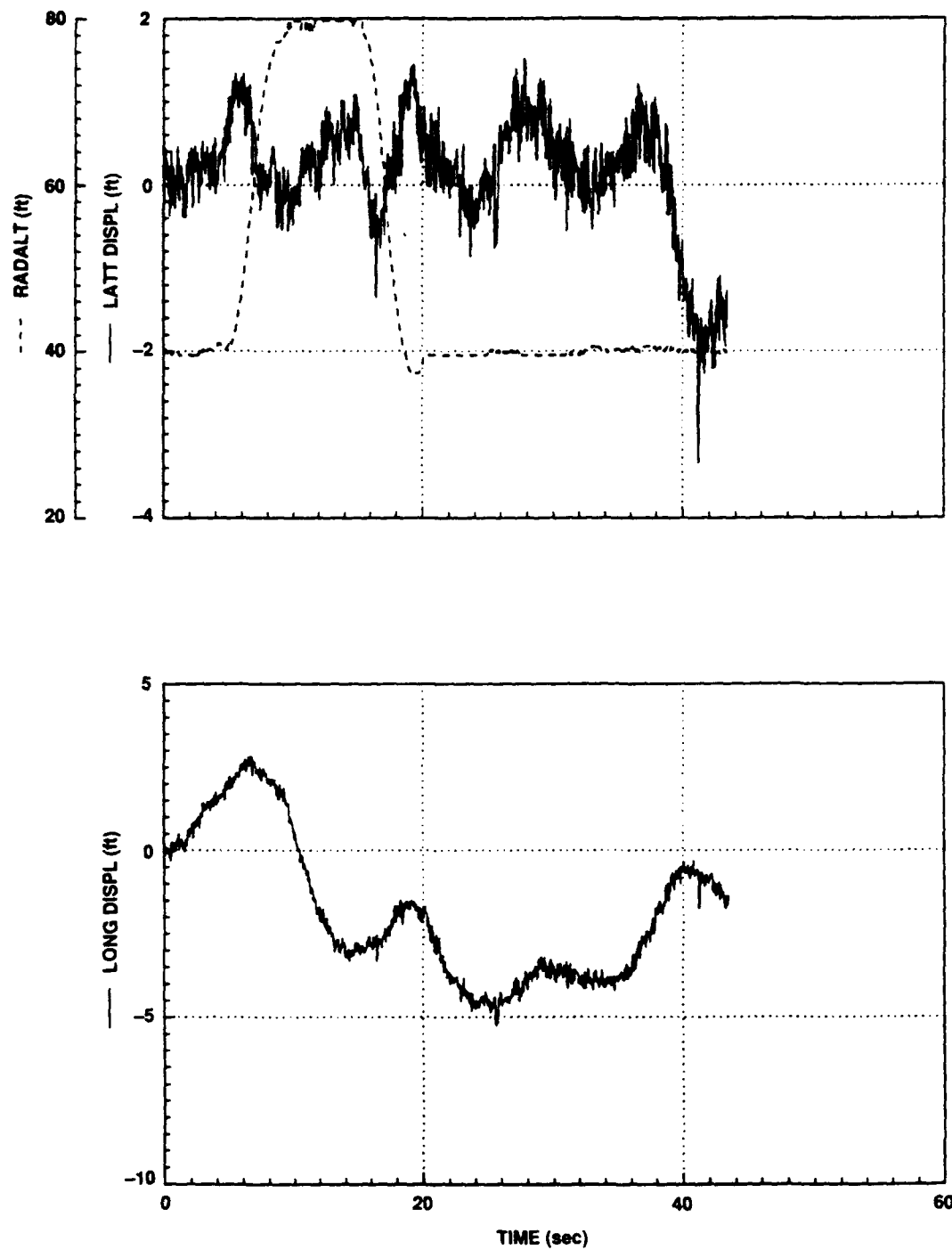
Figure C-2. Bob-up time history data for flight (Pilot 2) (Concluded).
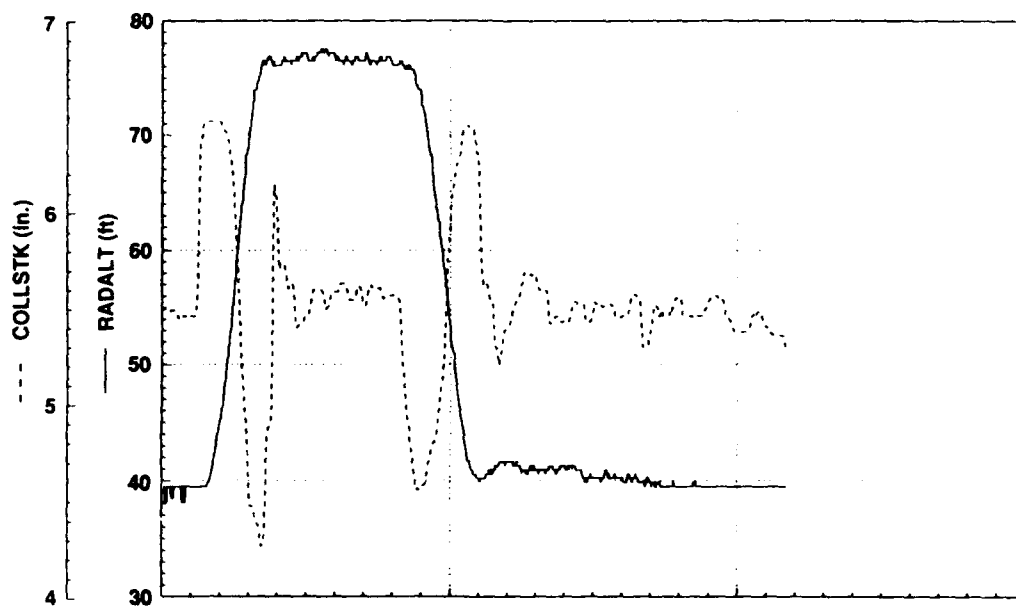
Figure C-3. Bob-up time history data for flight (Pilot 3).
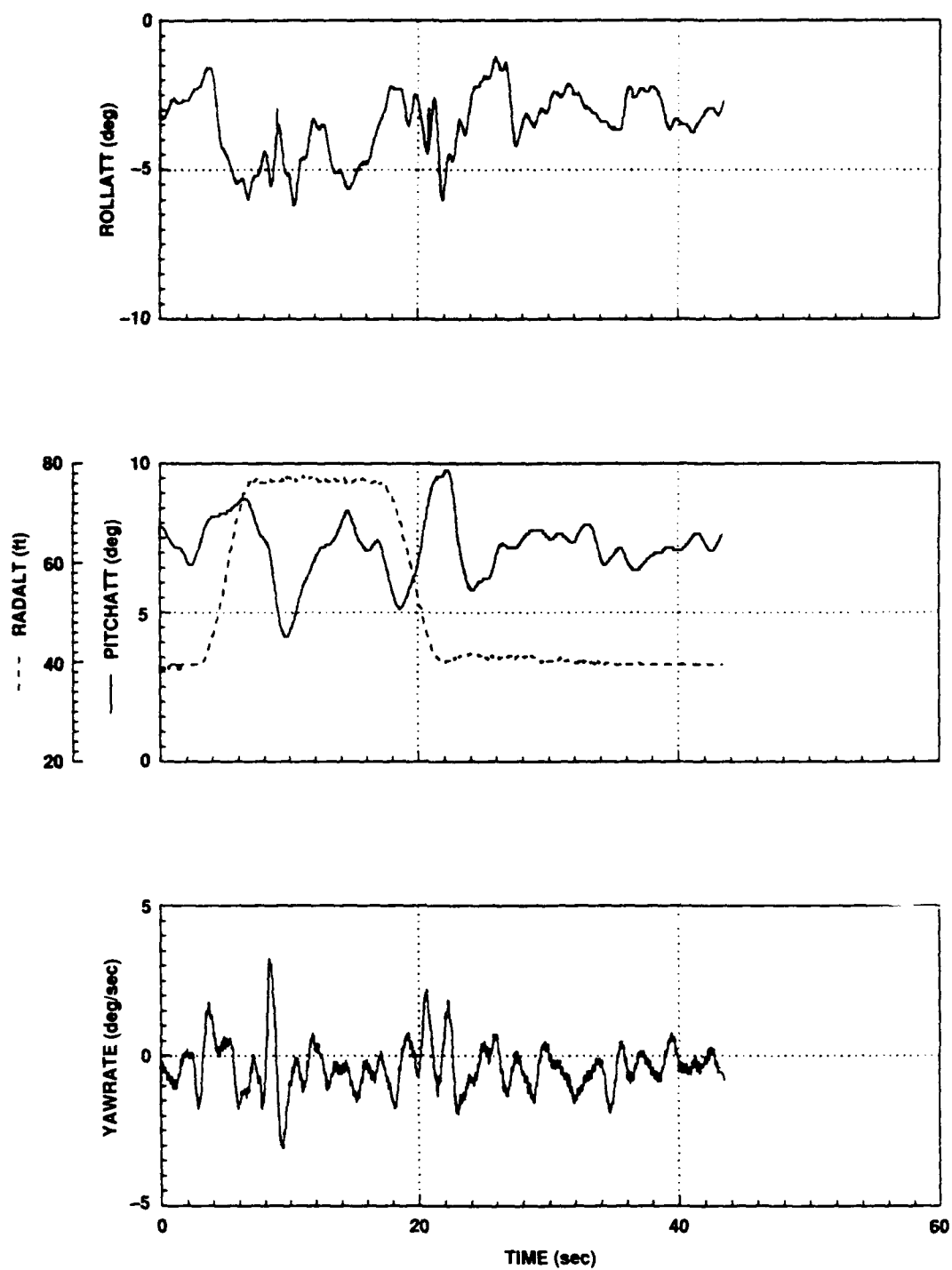
Figure C-3. Bob-up time history data for flight (Pilot 3) (Continued).
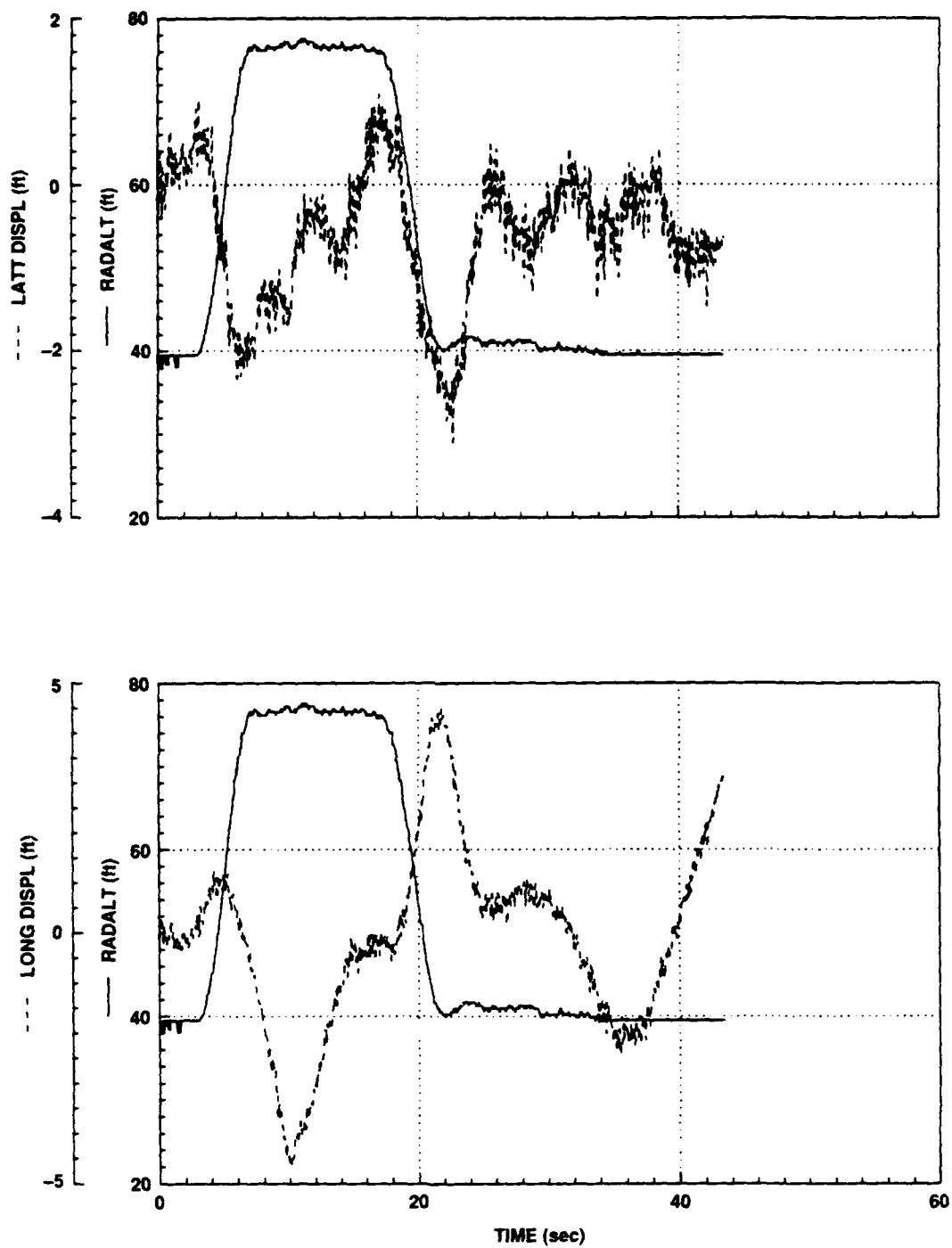
Figure C-3. Bob-up time history data for flight (Pilot 3) (Continued).

169

Figure C-3. Bob-up time history data for flight (Pilot 3) (Continued).
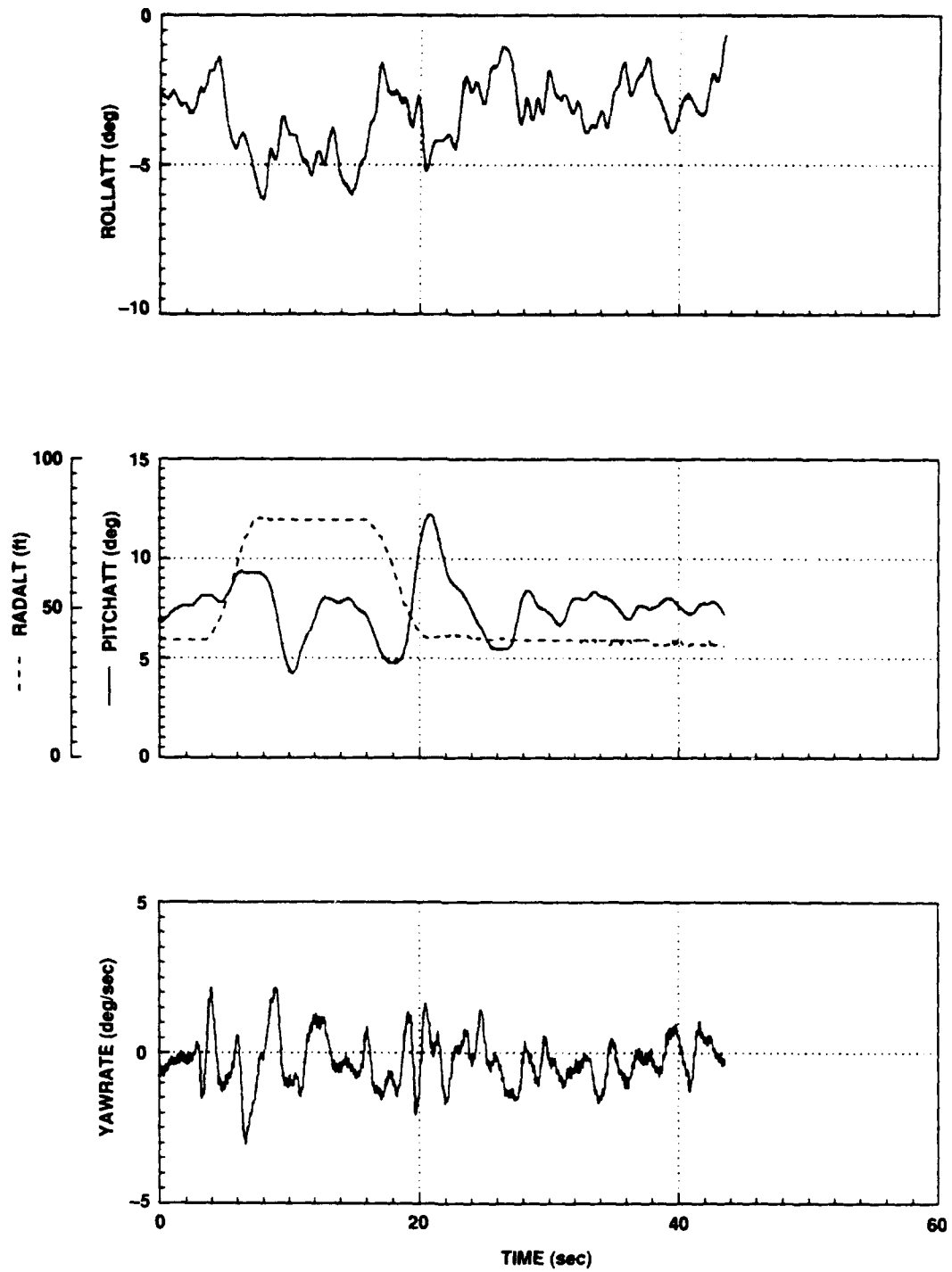
Figure C-3. Bob-up time history data for flight (Pilot 3) (Continued).
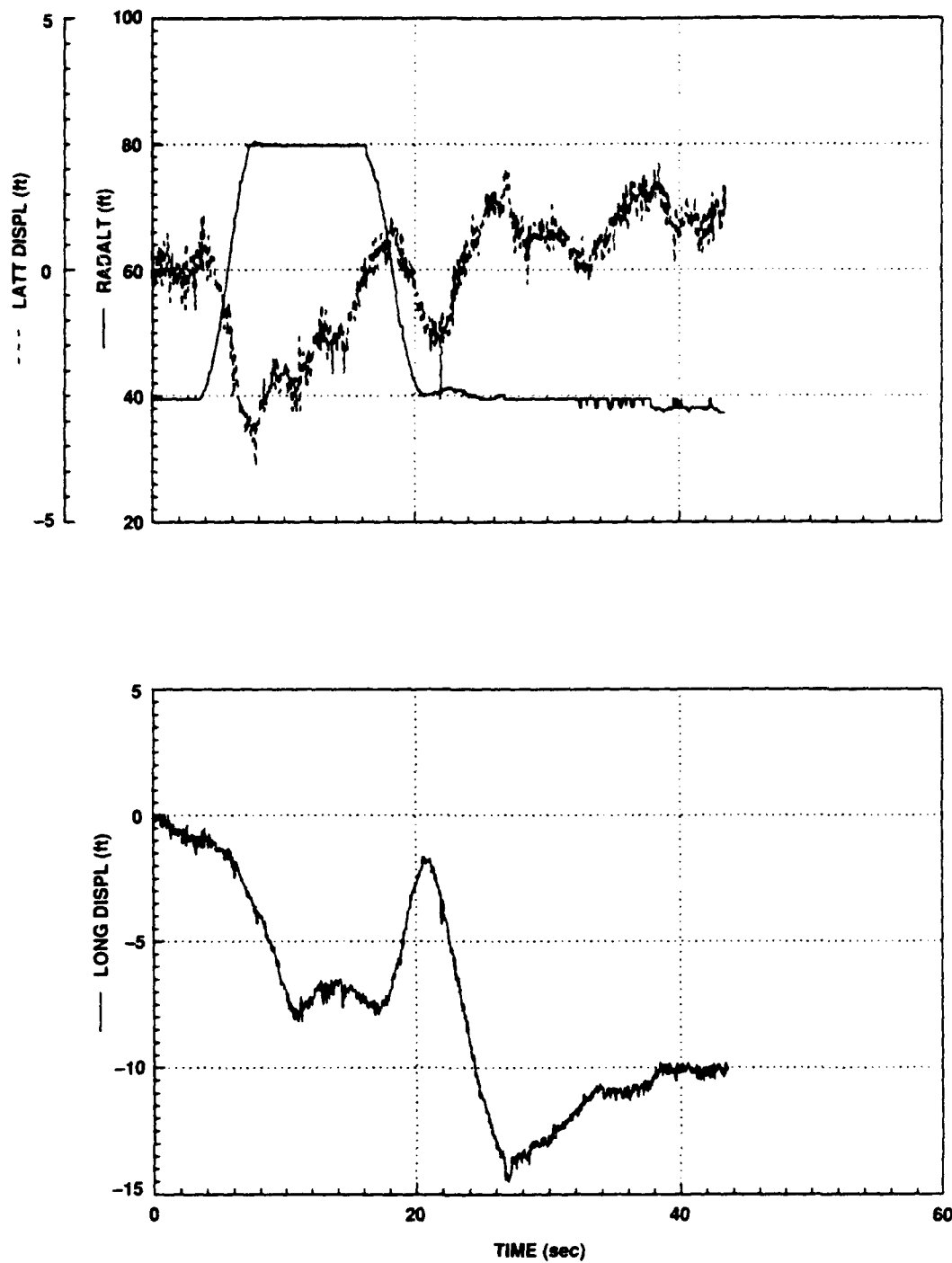
Figure C-3. Bob-up time history data for flight (Pilot 3) (Continued).
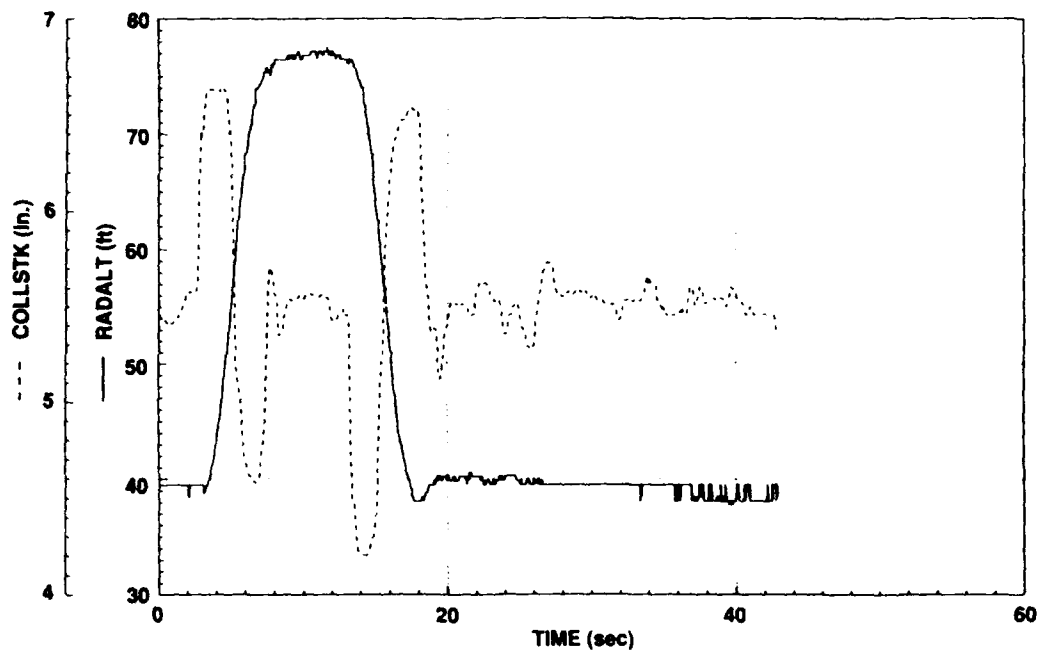
Figure C-3. Bob-up time history data for flight (Pilot 3) (Continued).
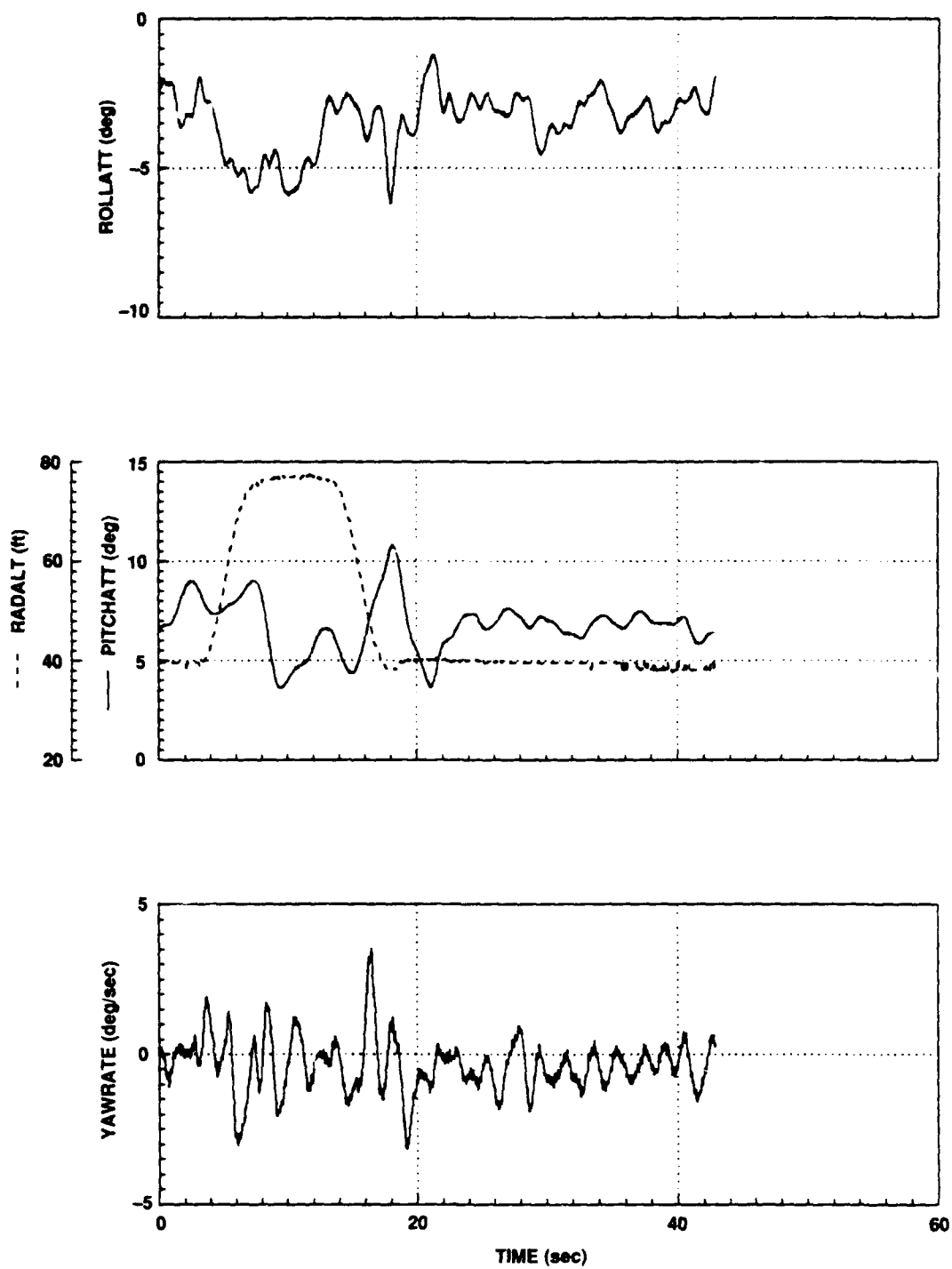
Figure C-3. Bob-up time history data for flight (Pilot 3) (Continued).
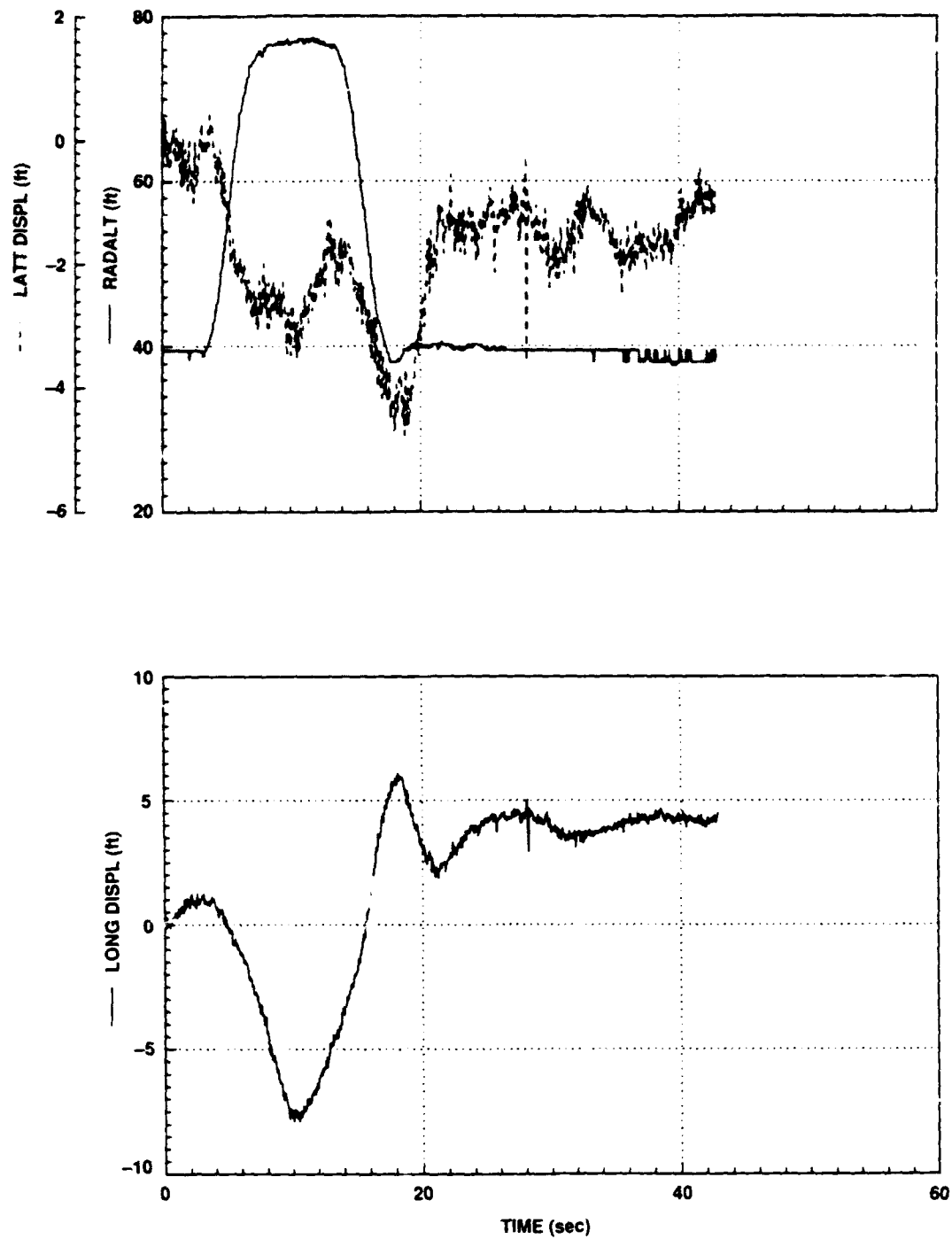
Figure C-3. Bob-up time history data for flight (Pilot 3) (Concluded).
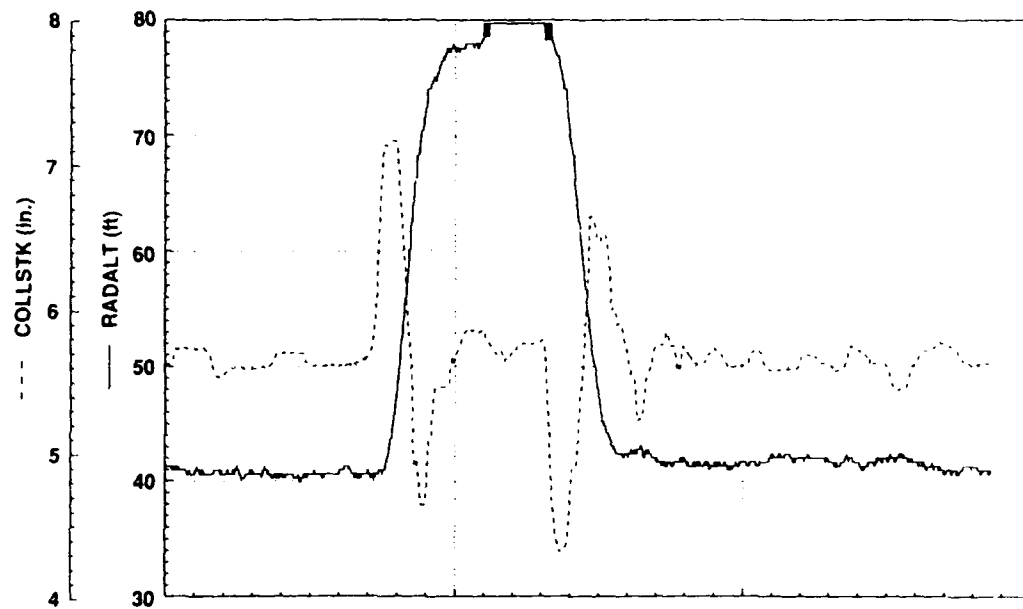
Figure C-4. Bob-up time history data for flight (Pilot 4).
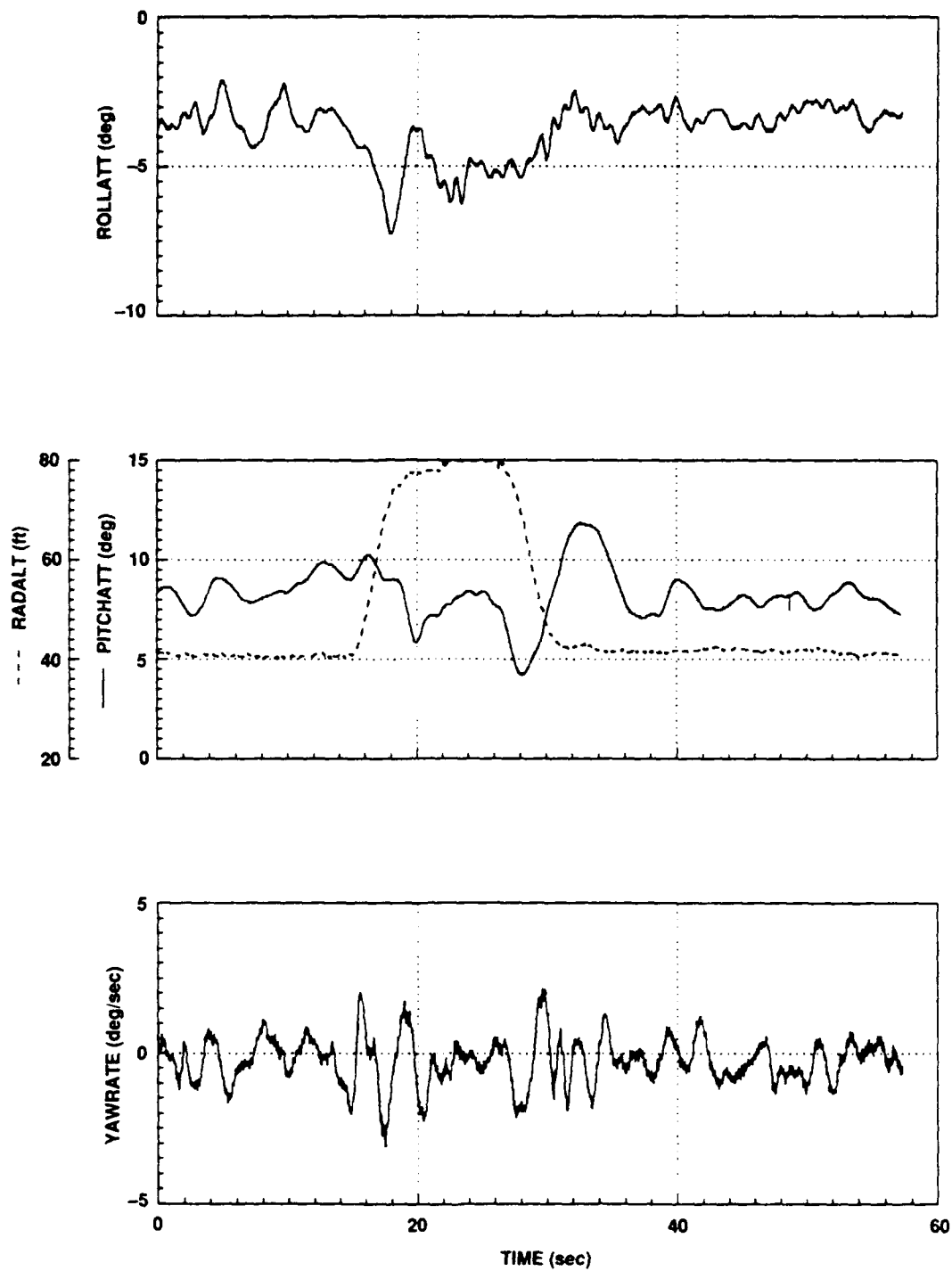
Figure C-4. Bob-up time history data for flight (Pilot 4) (Continued).
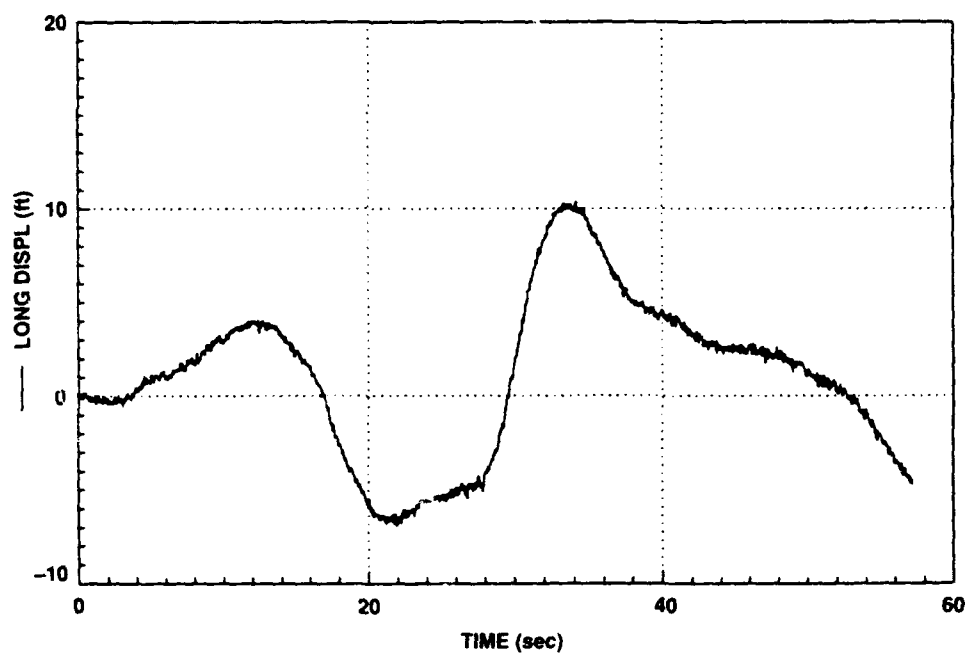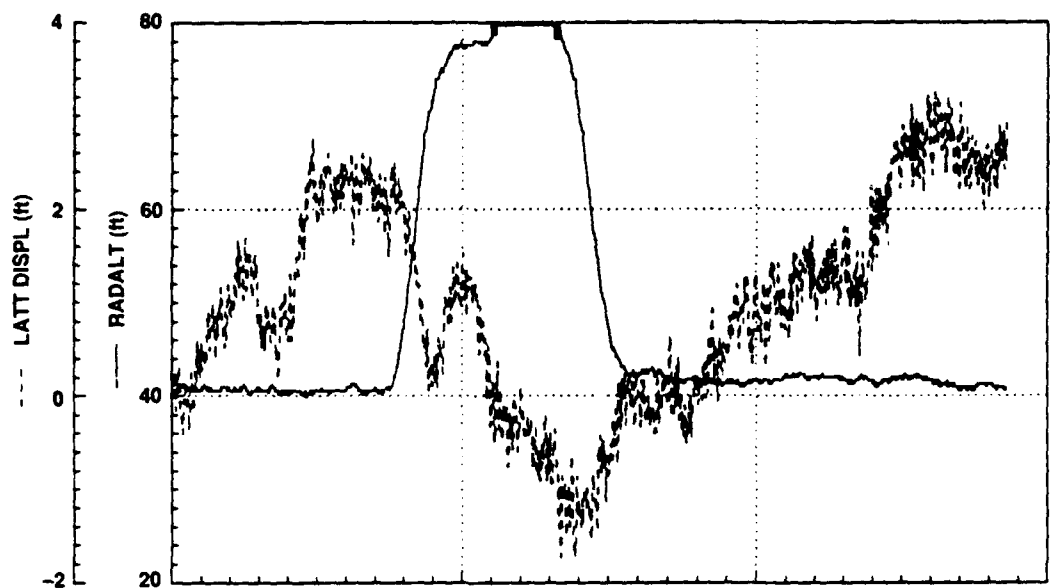
Figure C-4. Bob-up time history data for flight (Pilot 4) (Continued).

Figure C-4. Bob-up time history data for flight (Pilot 4) (Continued).
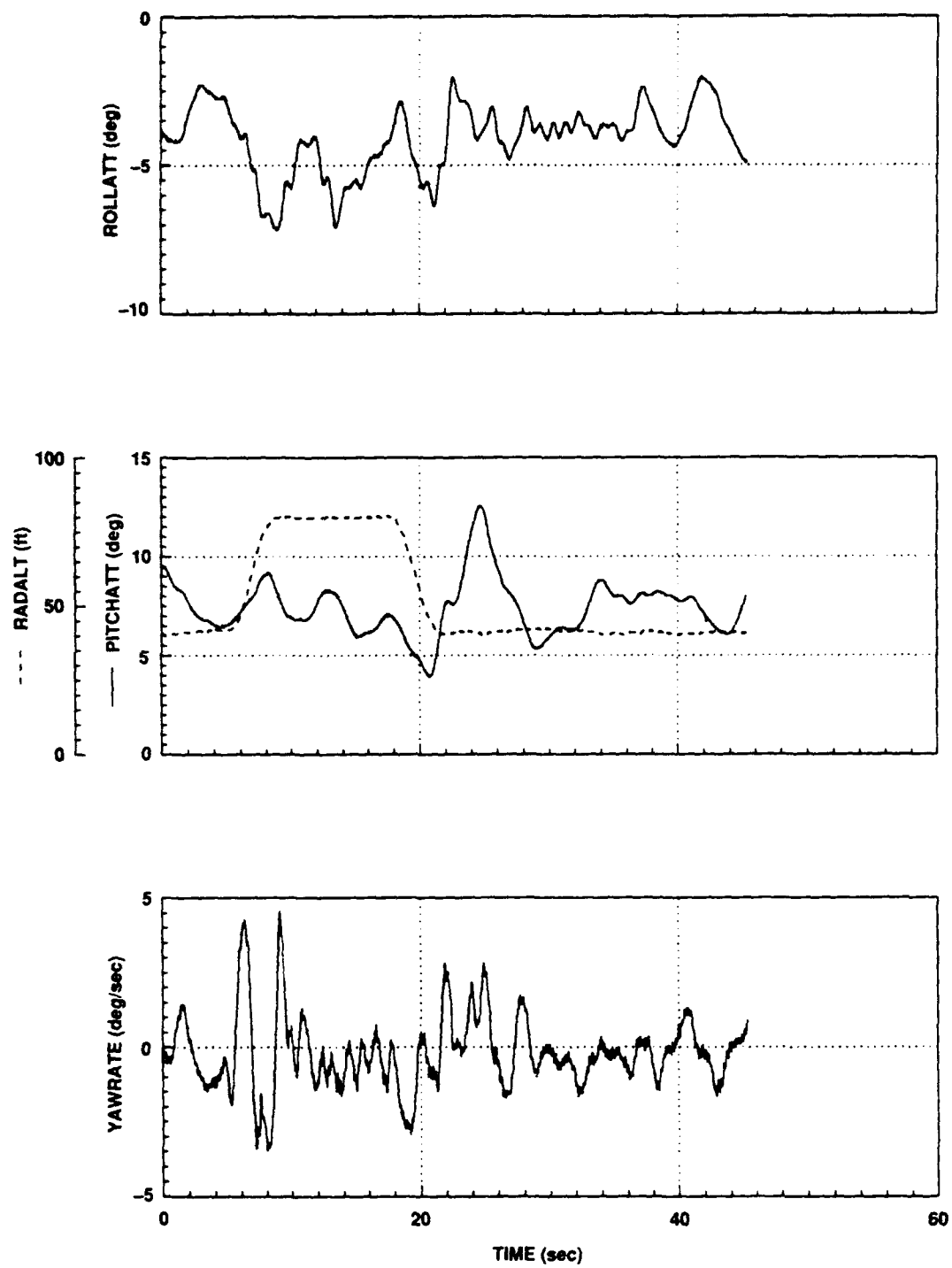
Figure C-4. Bob-up time history data for flight (Pilot 4) (Continued).
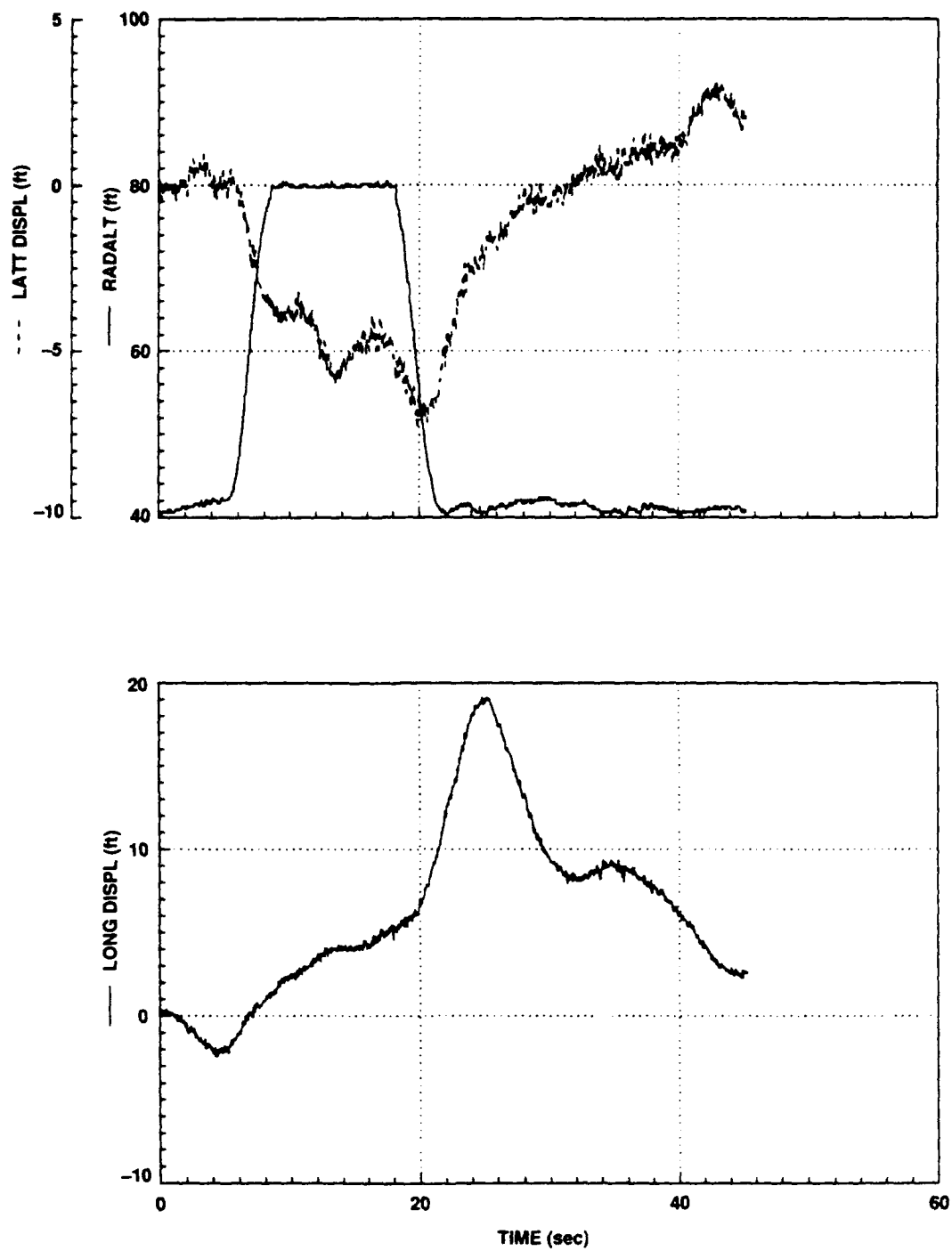
Figure C-4. Bob-up time history data for flight (Pilot 4) (Continued).
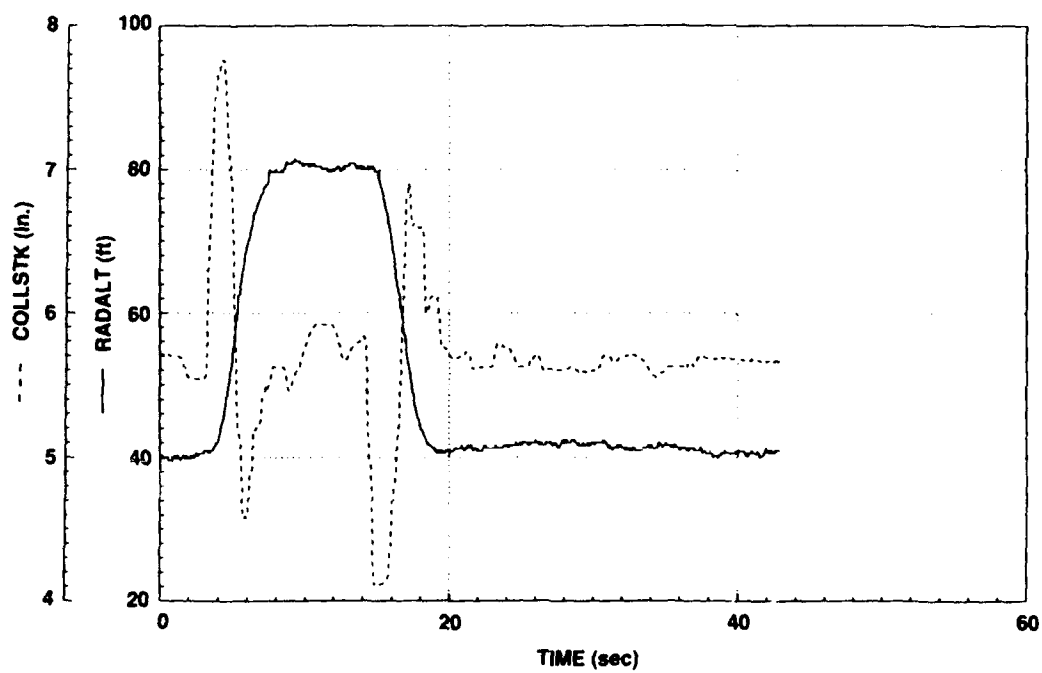
Figure C-4. Bob-up time history data for flight (Pilot 4) (Continued).
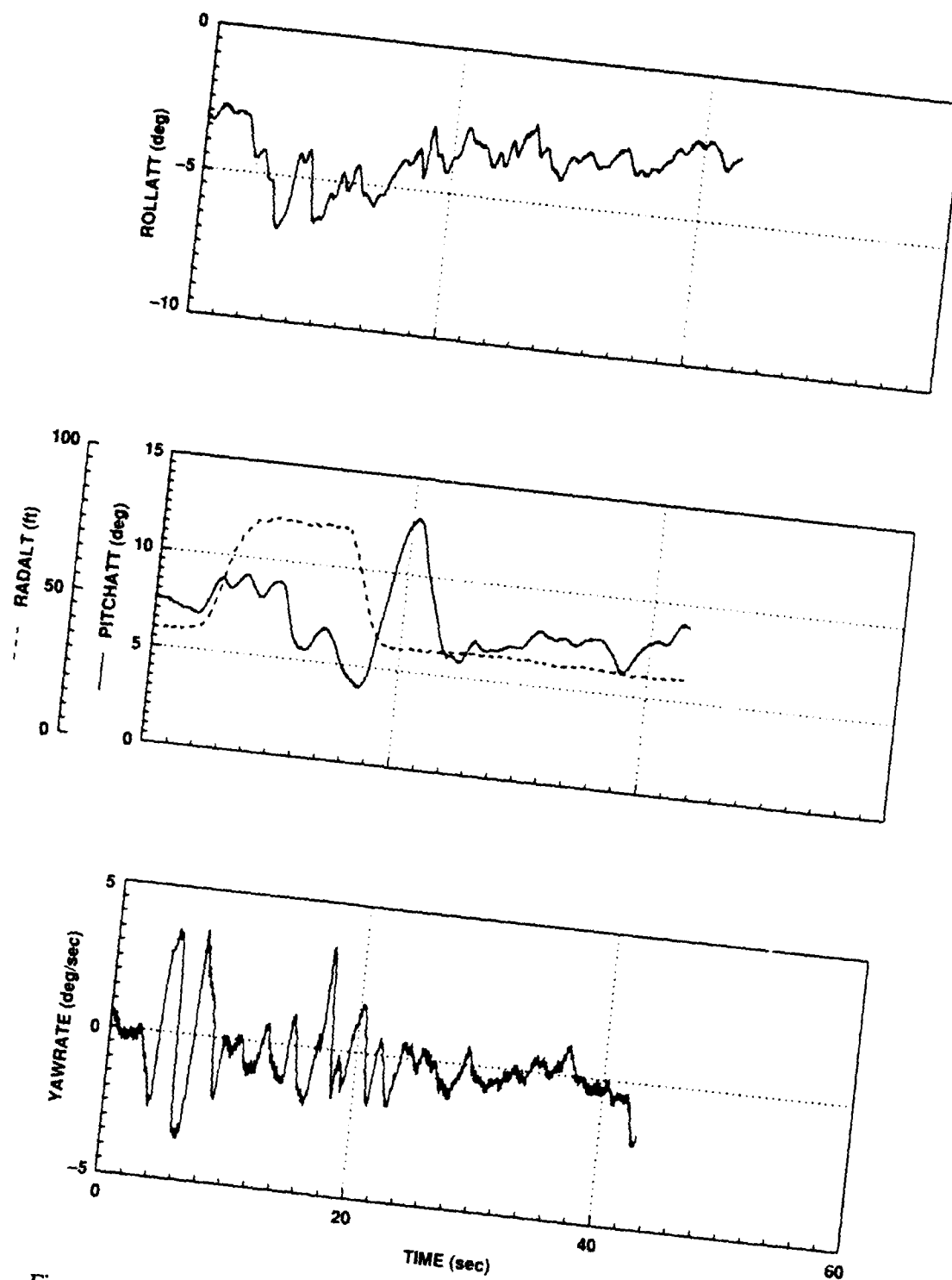
Figure C-4. Bob-up time history data for flight (Pilot 4) (Continued).
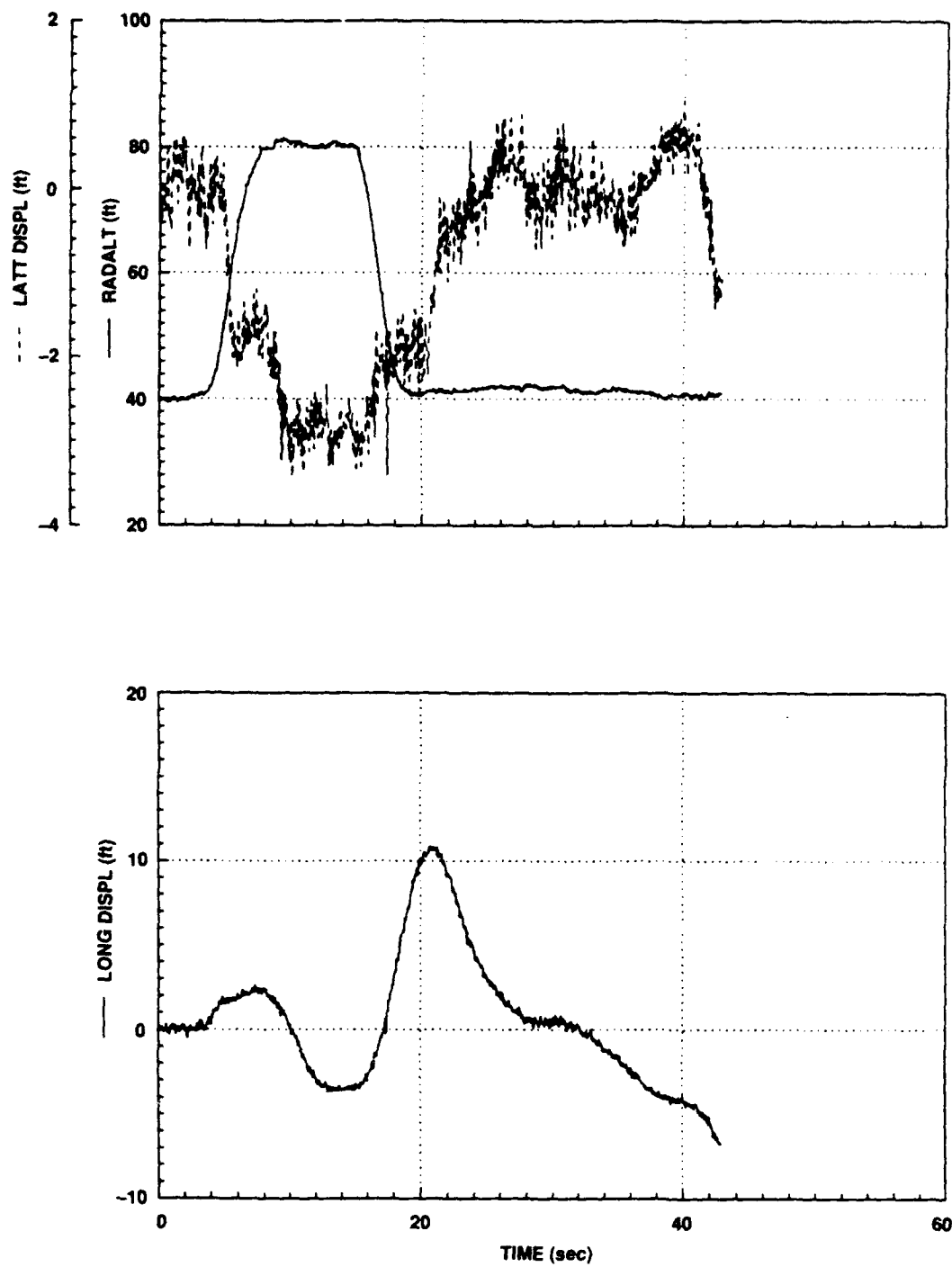
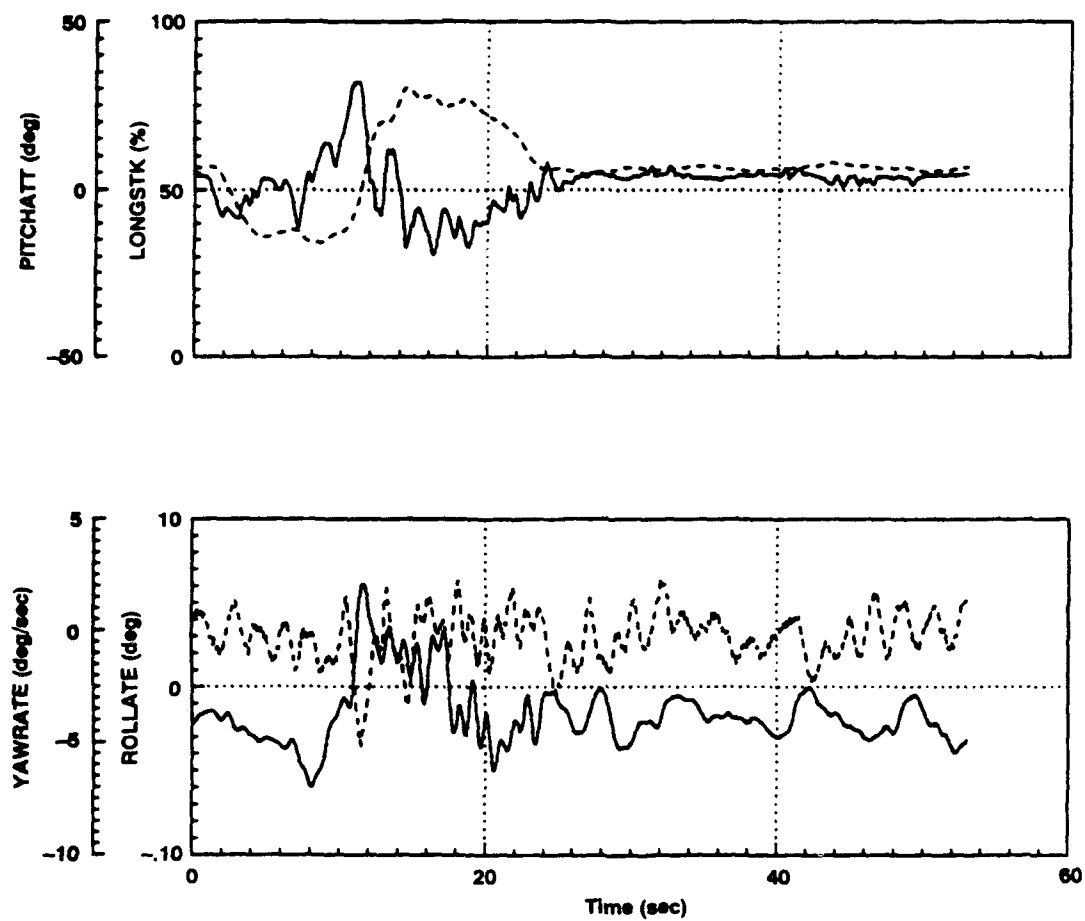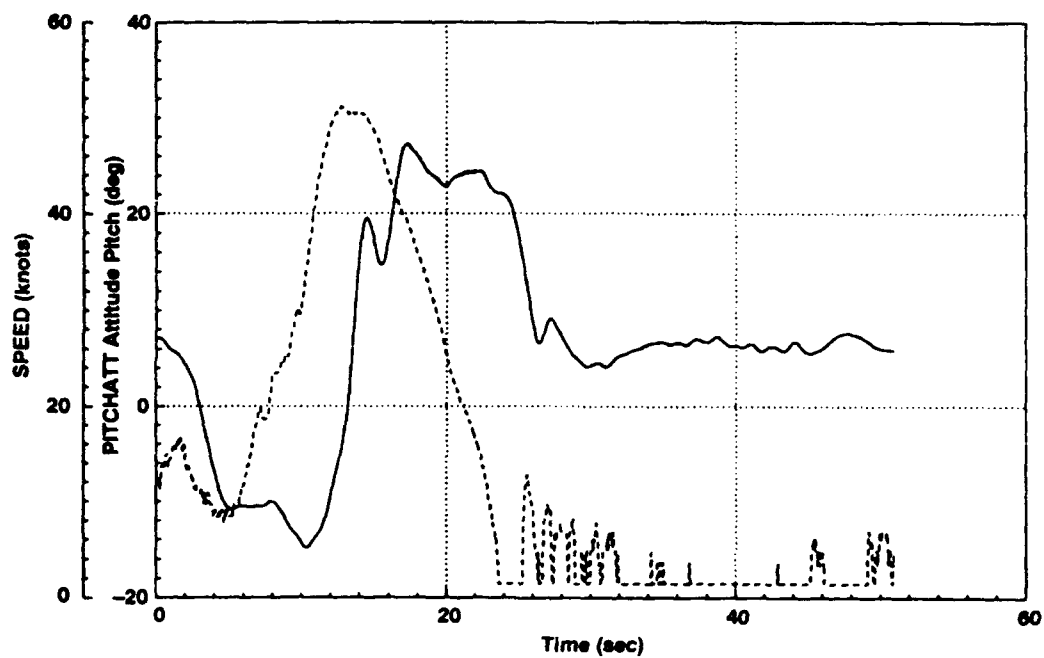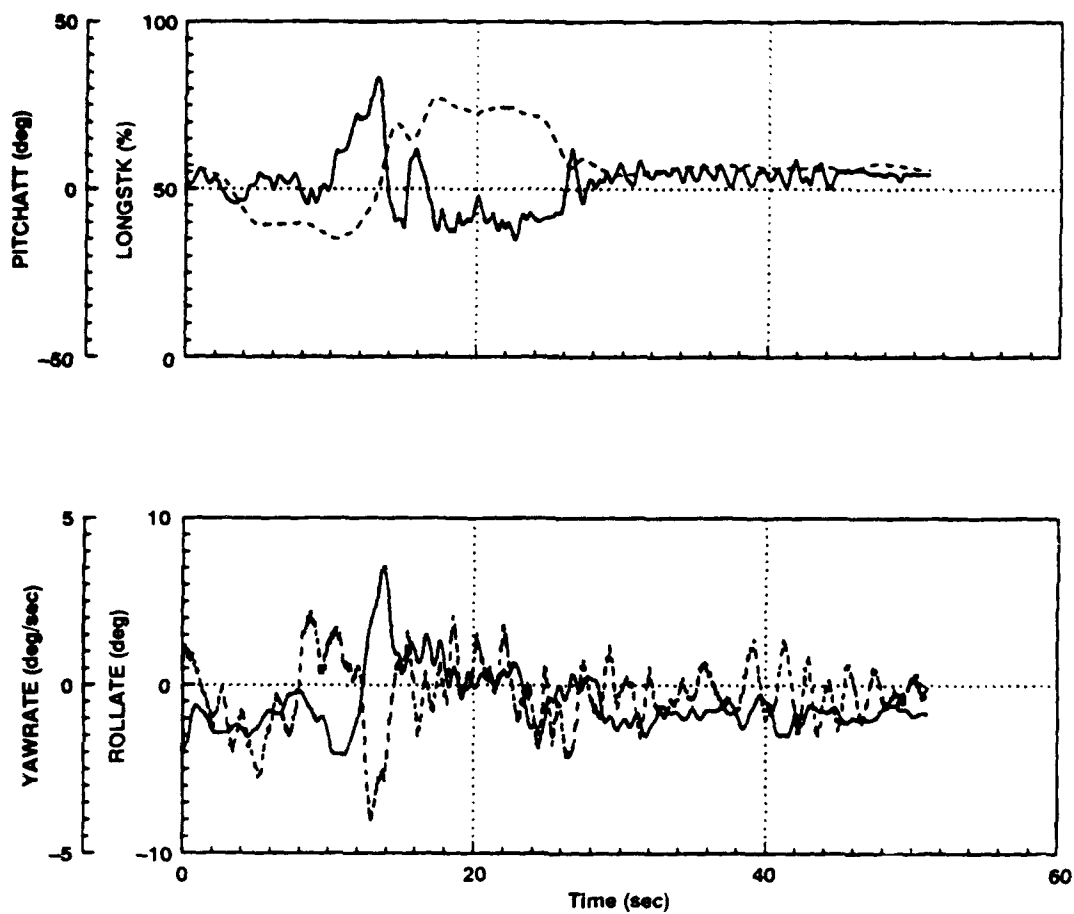Figure C-4. Bob-up time history data for flight (Pilot 4) (Concluded).
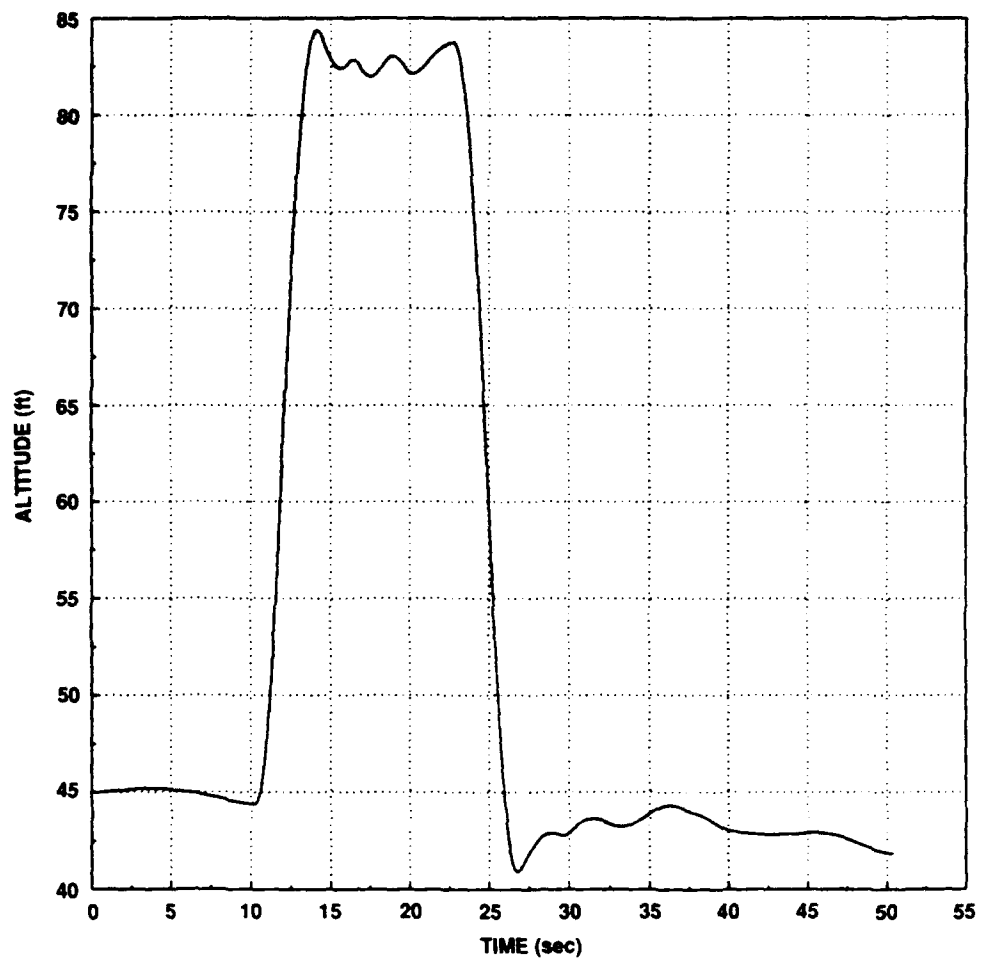
Figure C-5. Bob-up time history data for simulator (Pilot 2).
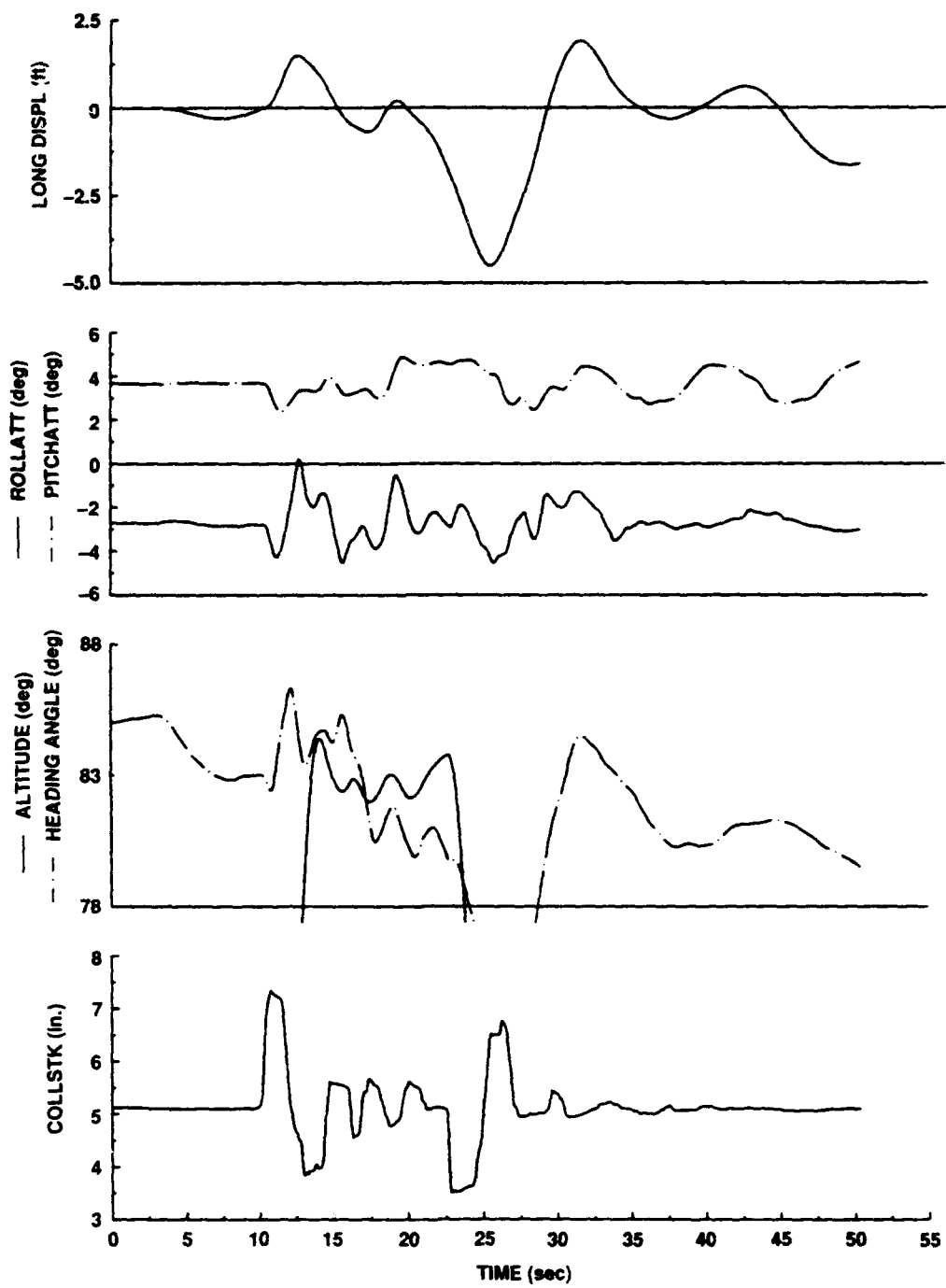
Figure C-5. Bob-up time history data for simulator (Pilot 2) (Continued).
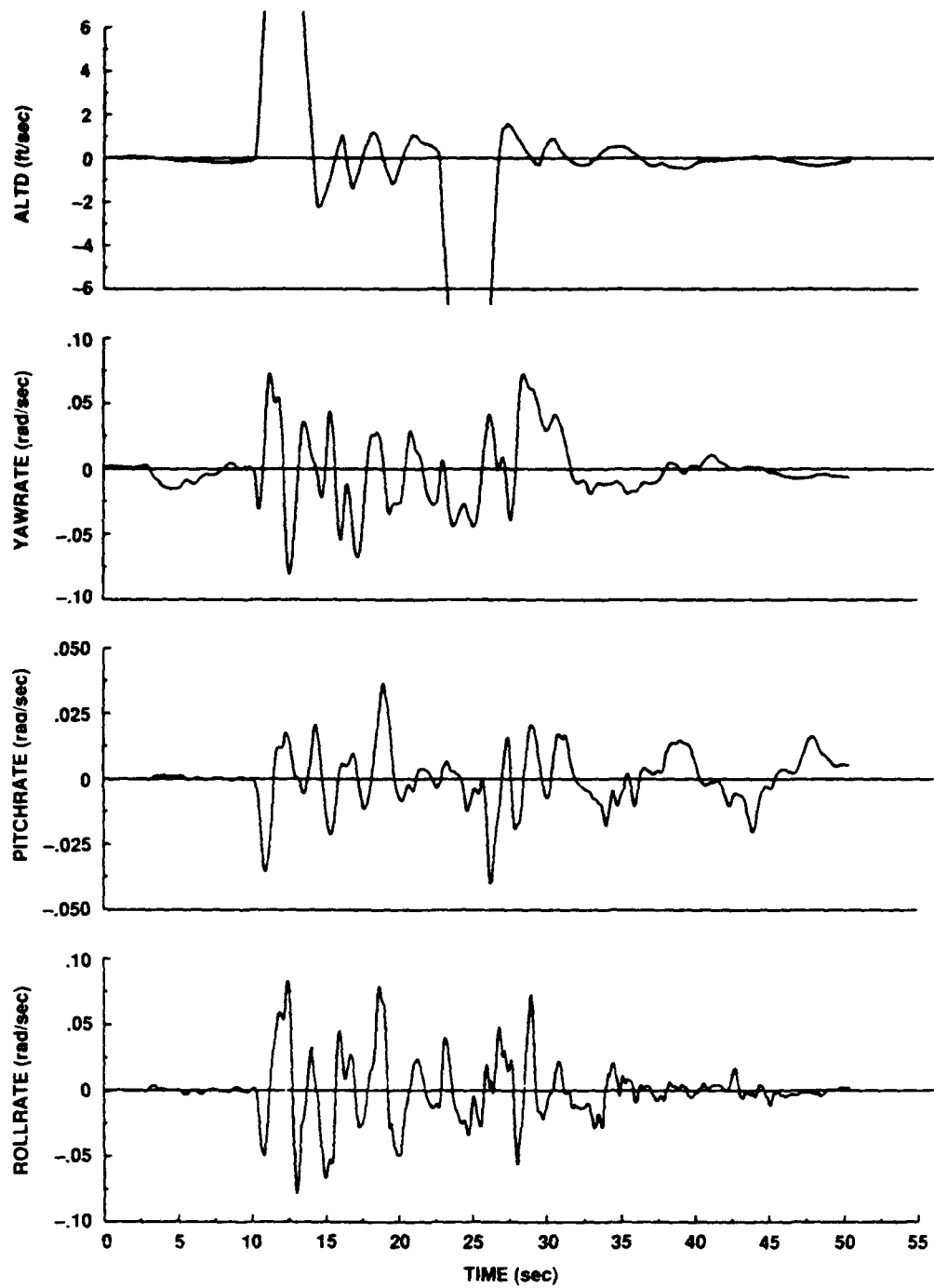
Figure C-5. Bob-up time history data for simulator (Pilot 2) (Continued).

Figure C-5. Bob-up time history data for simulator (Pilot 2) (Continued).

188

Figure C-5. Bob-up time history data for simulator (Pilot 2) (Continued).

Figure C-5. Bob-up time history data for simulator (Pilot 2) (Continued).

190
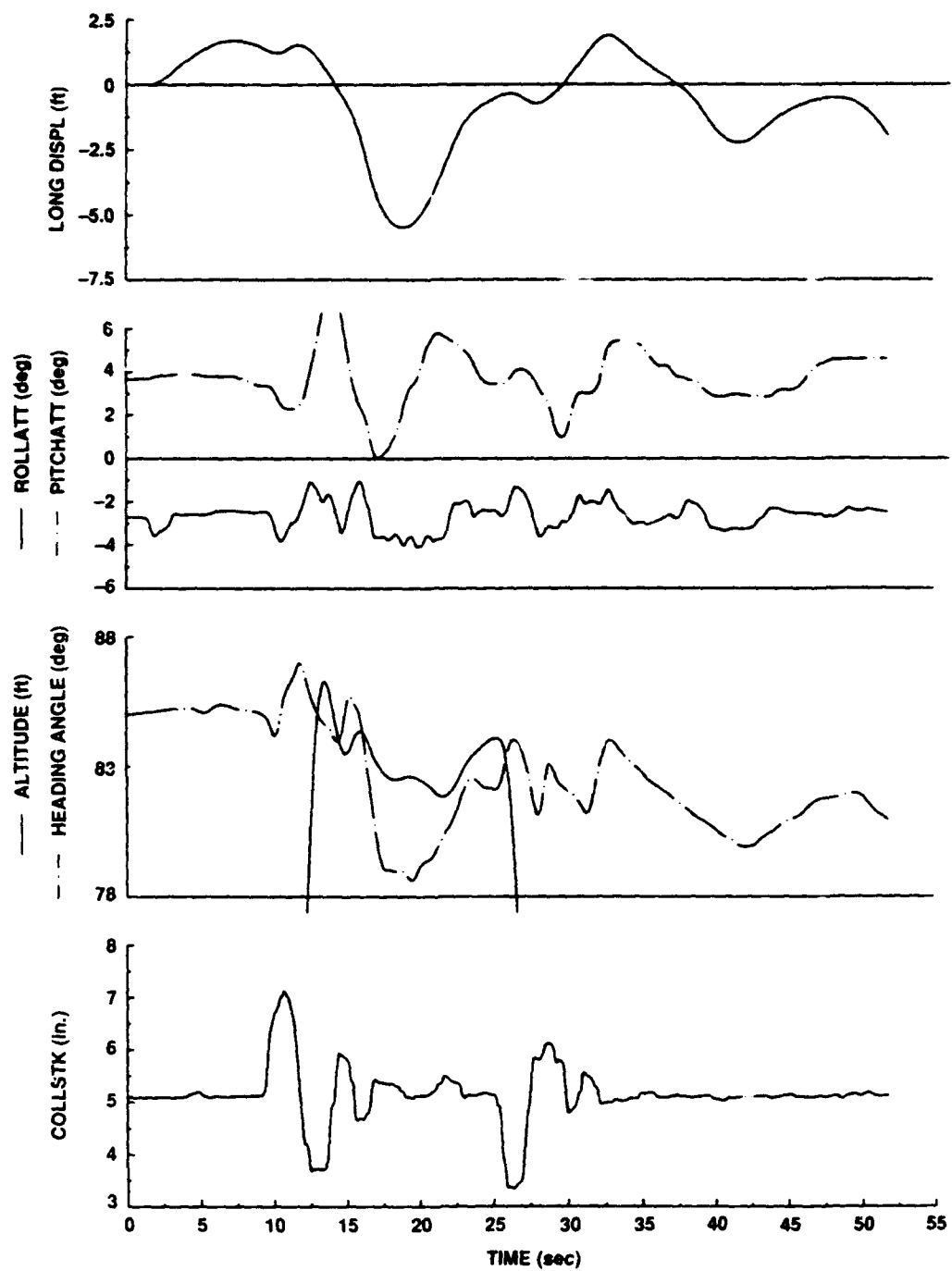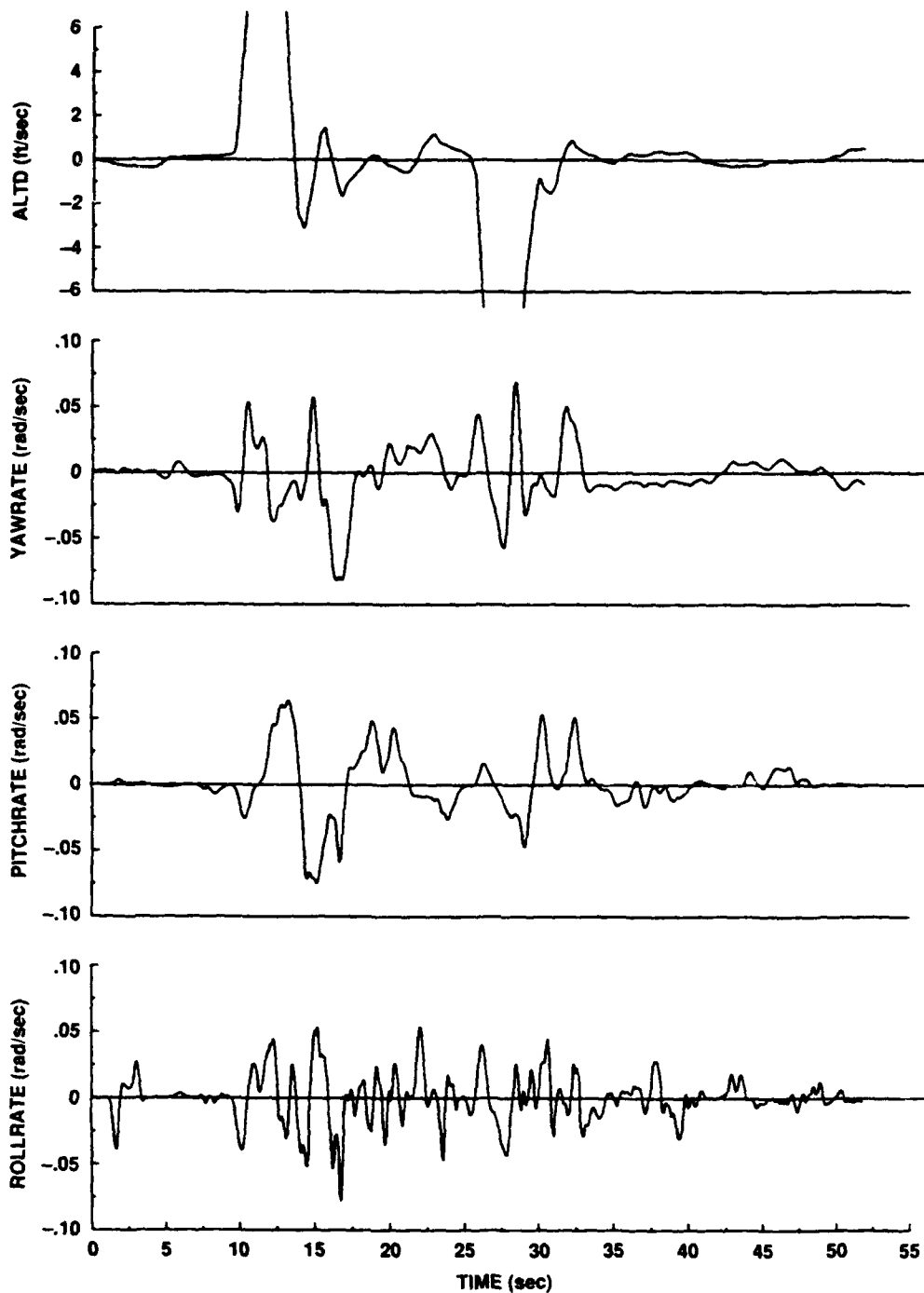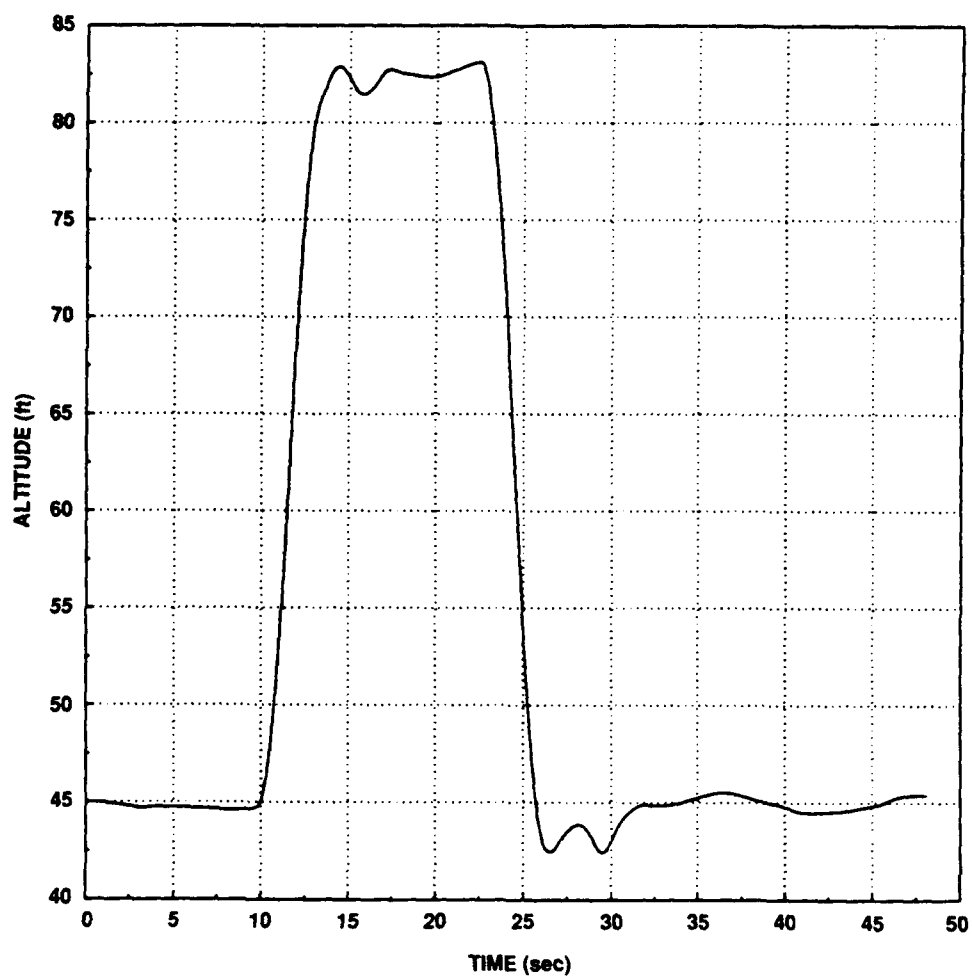
Figure C-5. Bob-up time history data for simulator (Pilot 2) (Continued).

Figure C-5. Bob-up time history data for simulator (Pilot 2) (Continued).
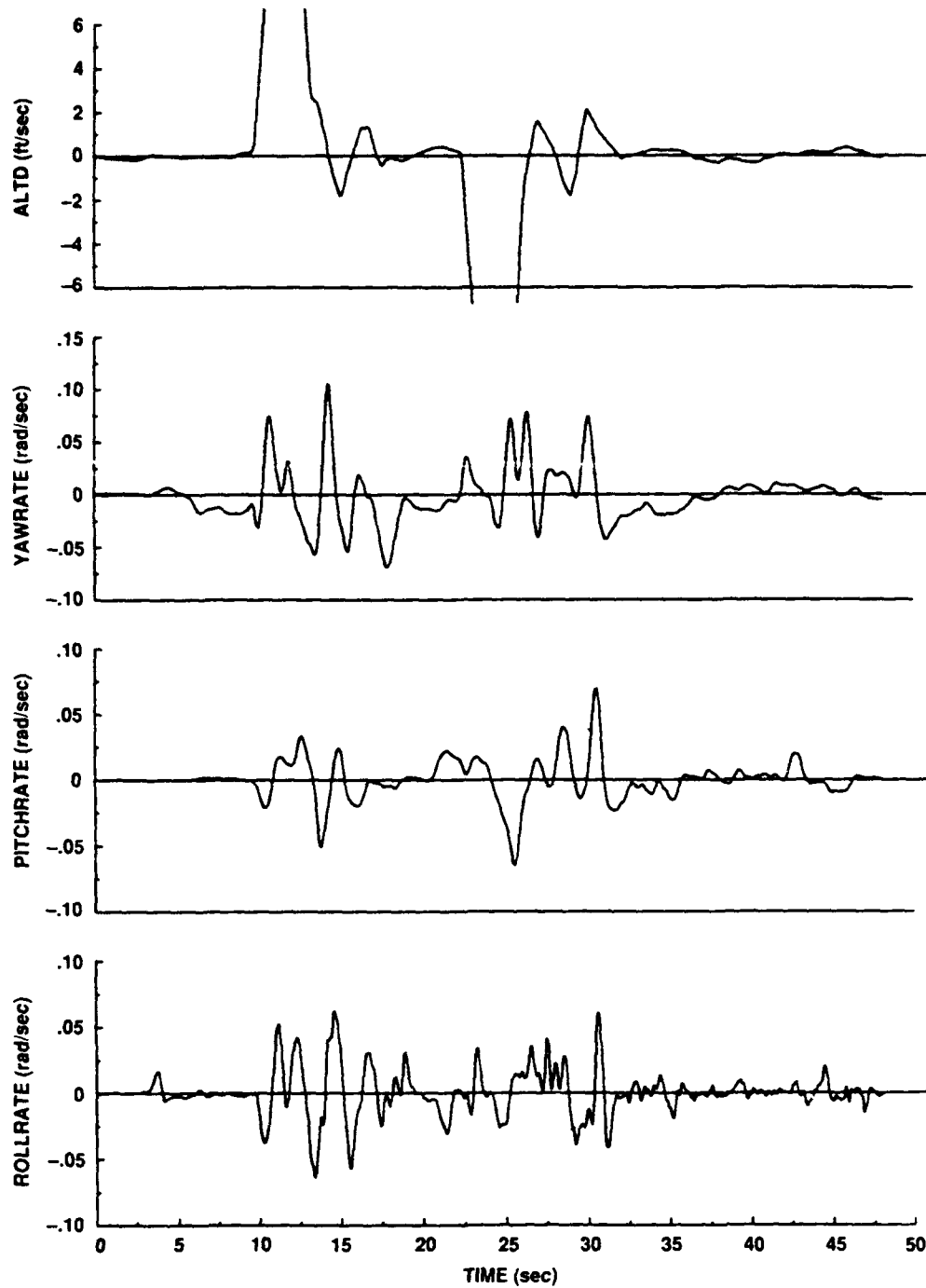
Figure C-5. Bob-up time history data for simulator (Pilot 2) (Concluded).

Figure C-6. Bob-up time history data for simulator (Pilot 4).
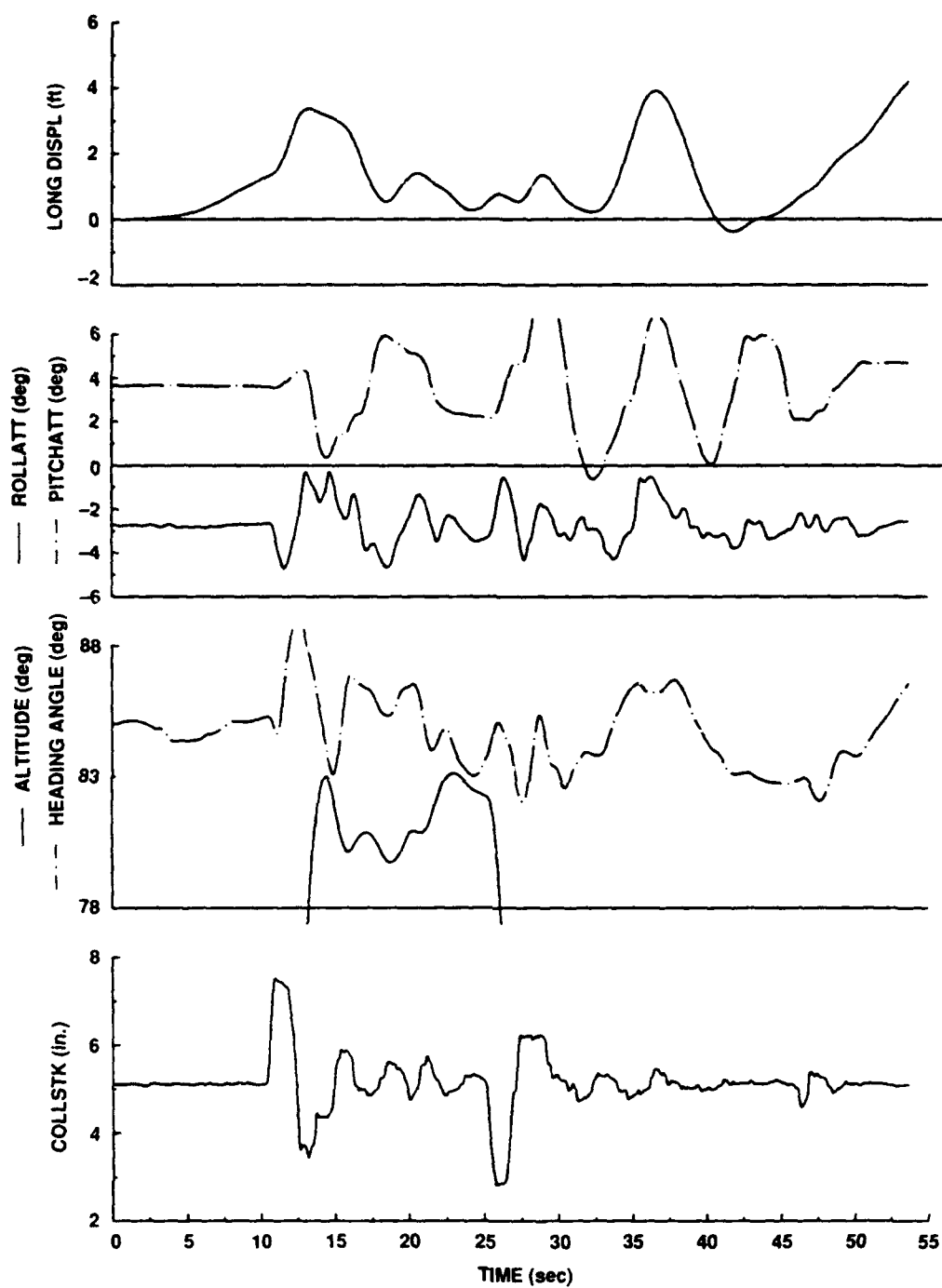
194

Figure C-6. Bob-up time history data for simulator (Pilot 4) (Continued).
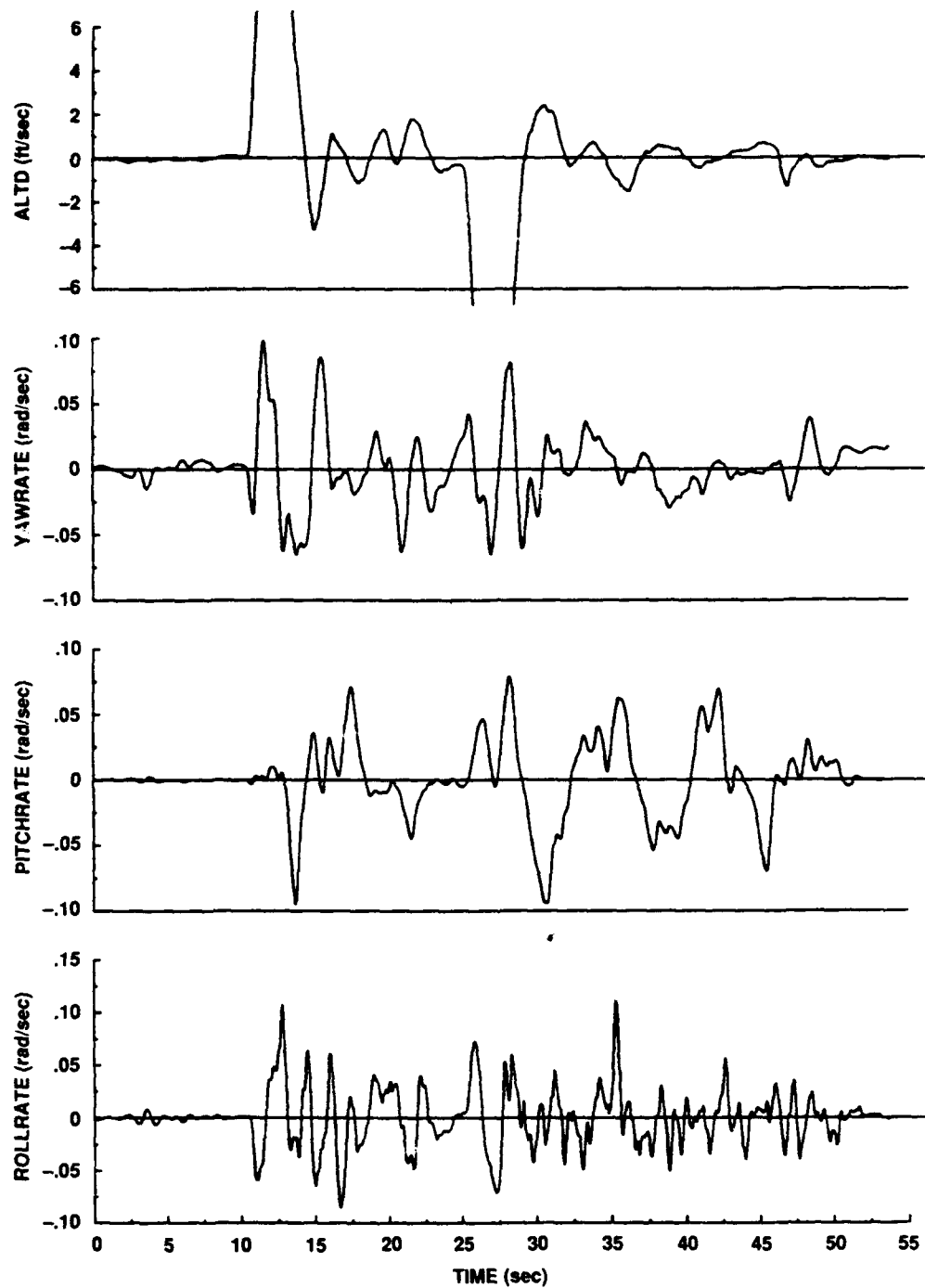
195

Figure C-6. Bob-up time history data for simulator (Pilot 4) (Continued).

Figure C-6. Bob-up time history data for simulator (Pilot 4) (Continued).
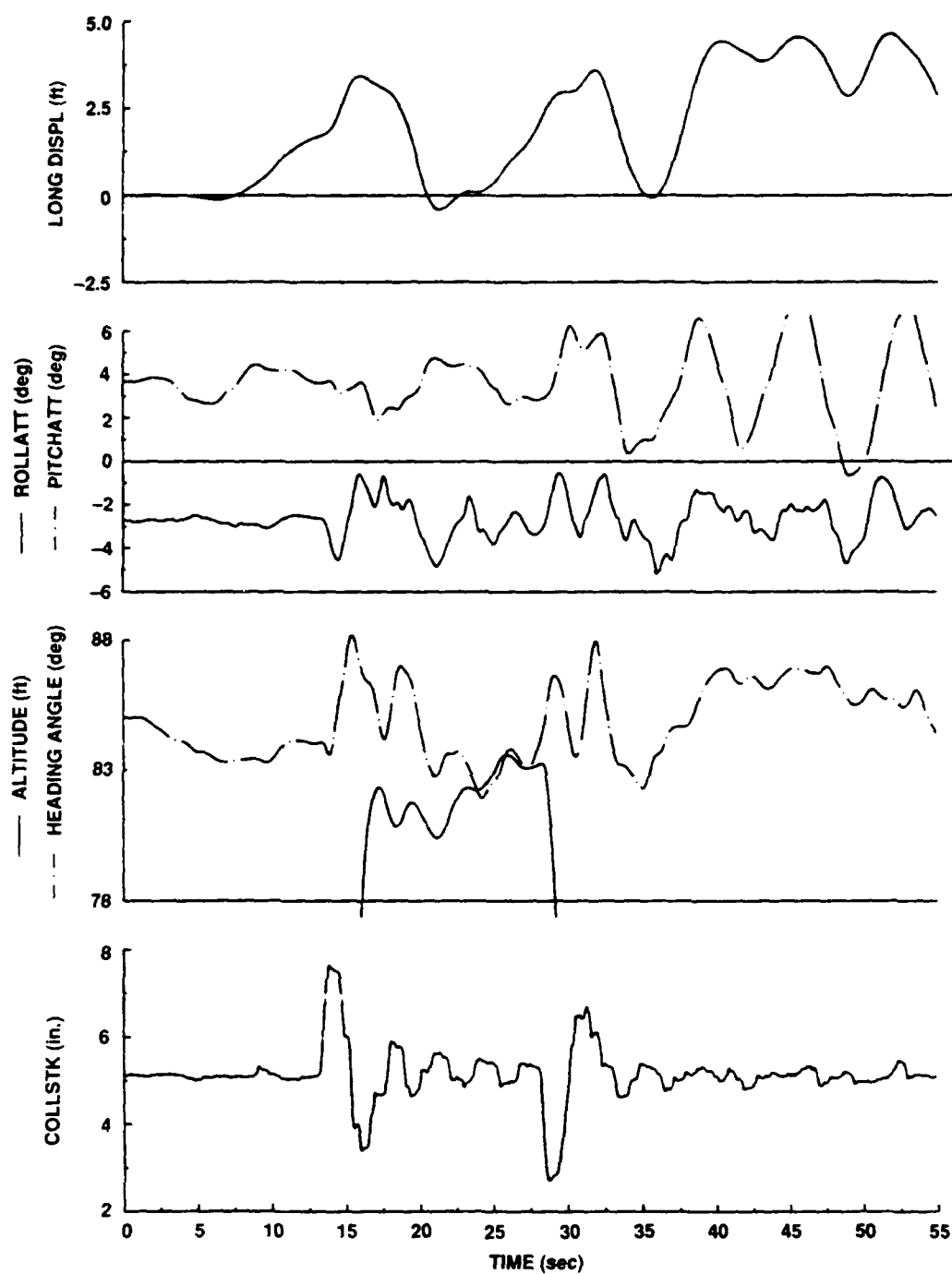
Figure C-6. Bob-up time history data for simulator (Pilot 4) (Continued).
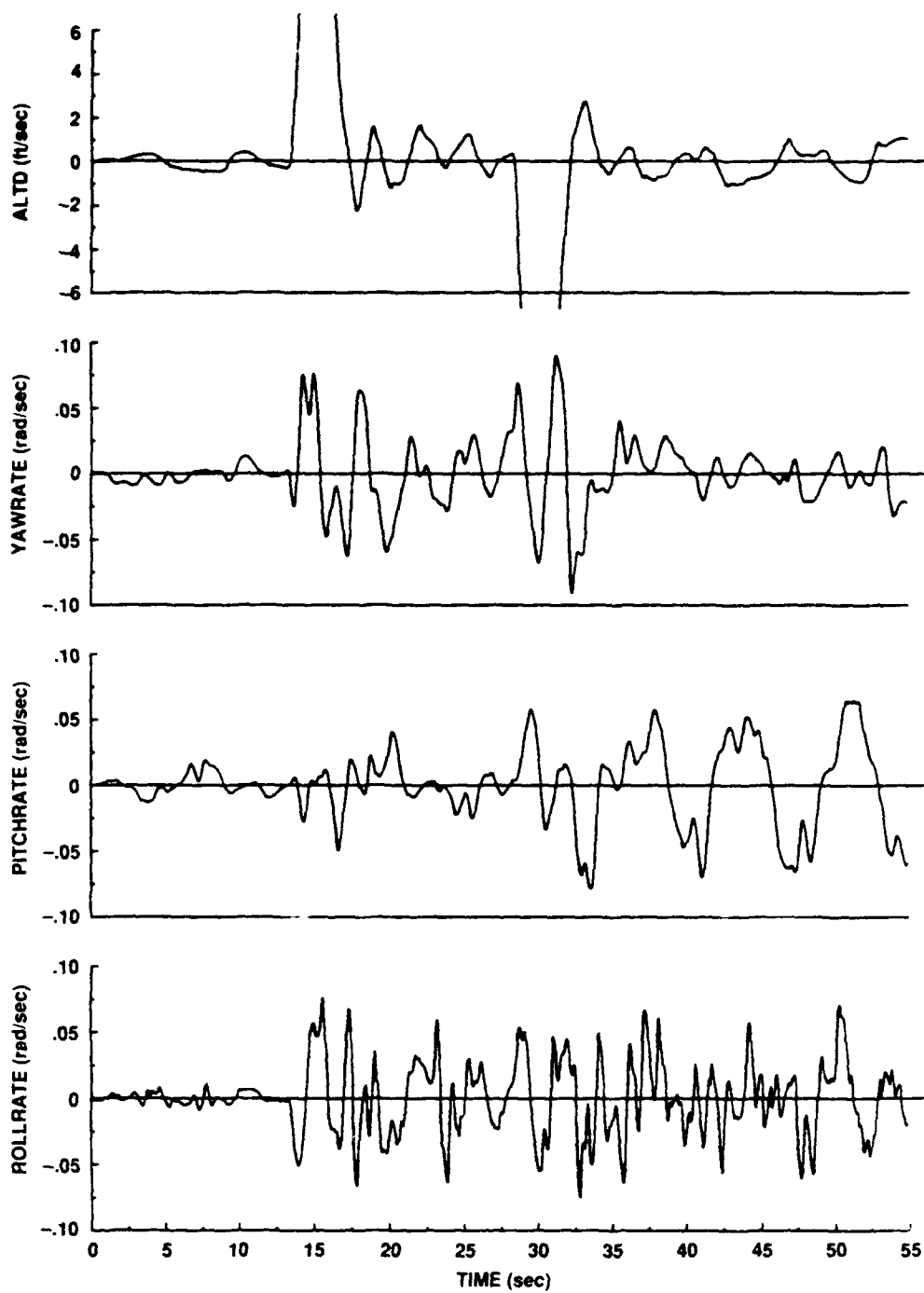
Figure C-6. Bob-up time history data for simulator (Pilot 4) (Continued).
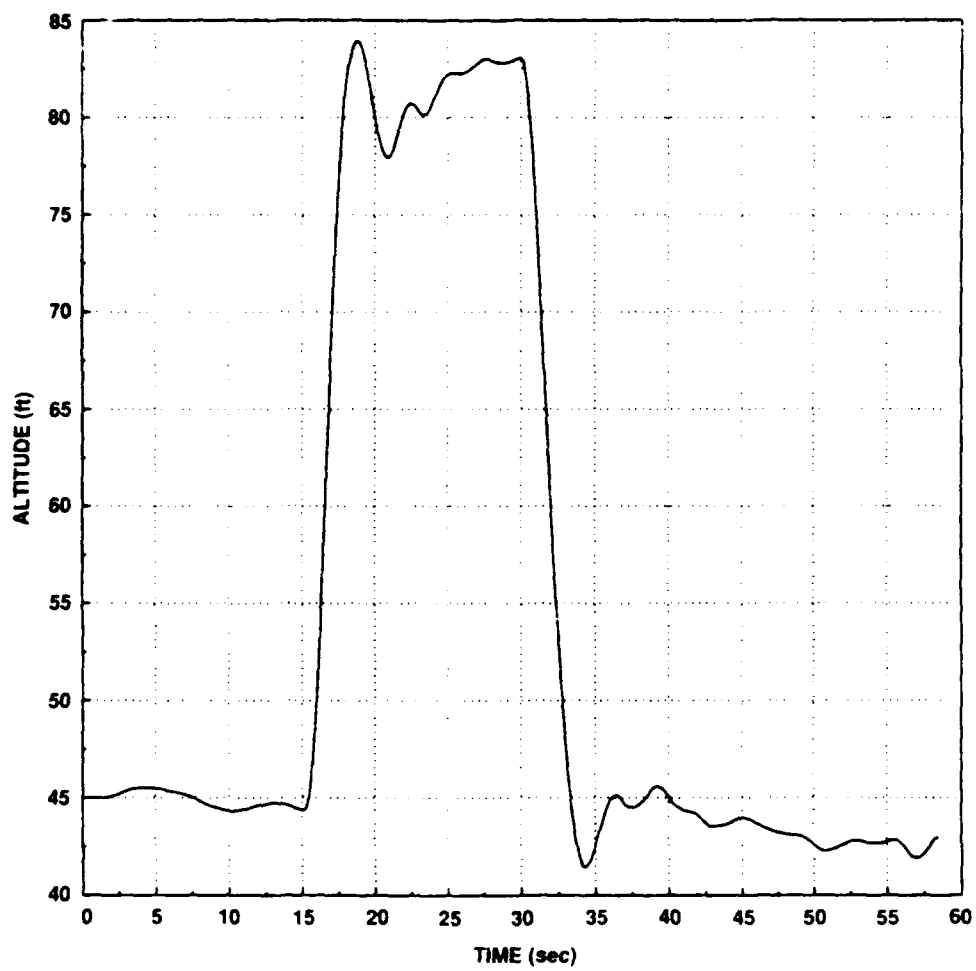
Figure C-6. Bob-up time history data for simulator (Pilot 4) (Continued).

Figure C-6. Bob-up time history data for simulator (Pilot 4) (Continued).
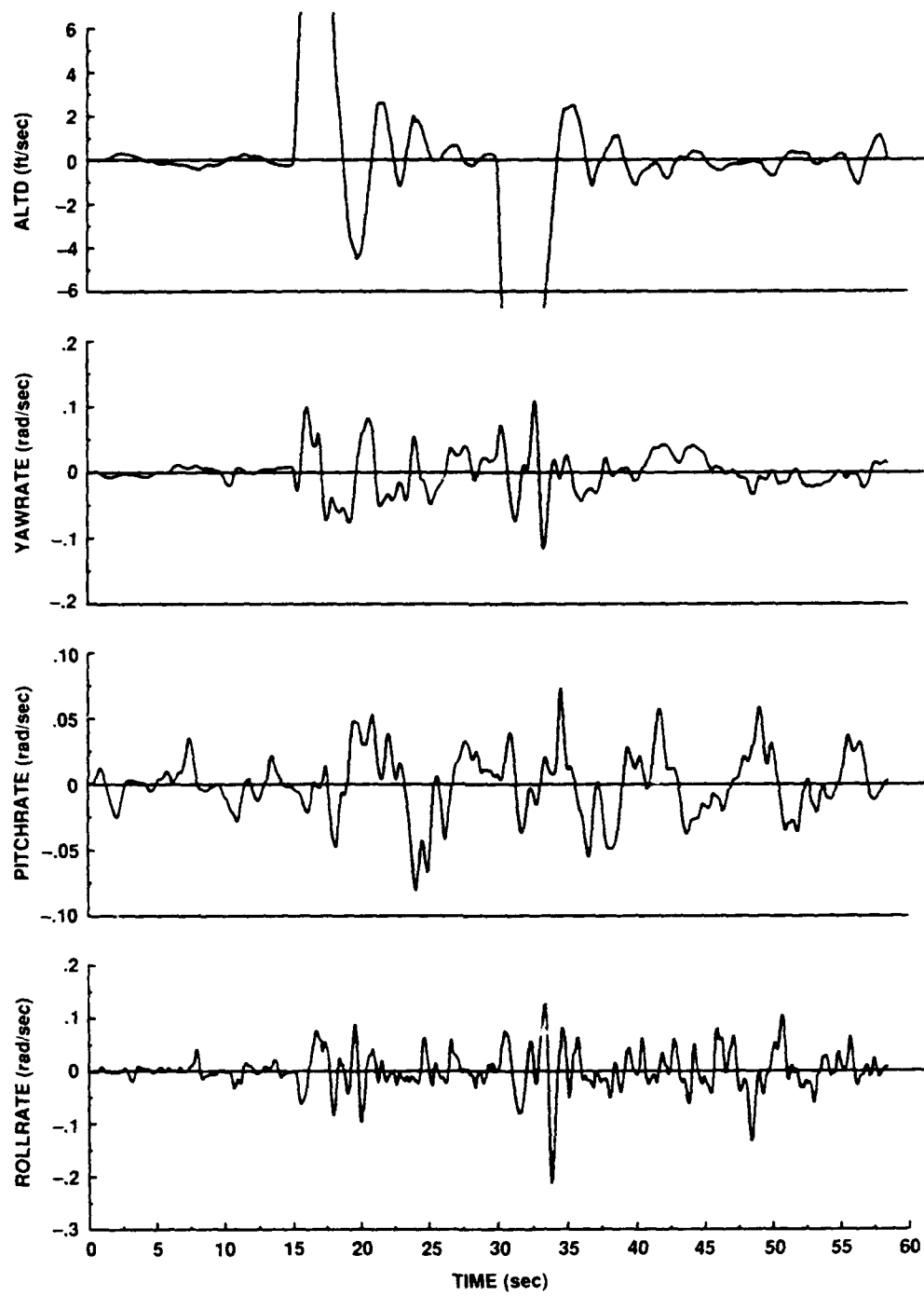
Figure C-6. Bob-up time history data for simulator (Pilot 4) (Concluded).
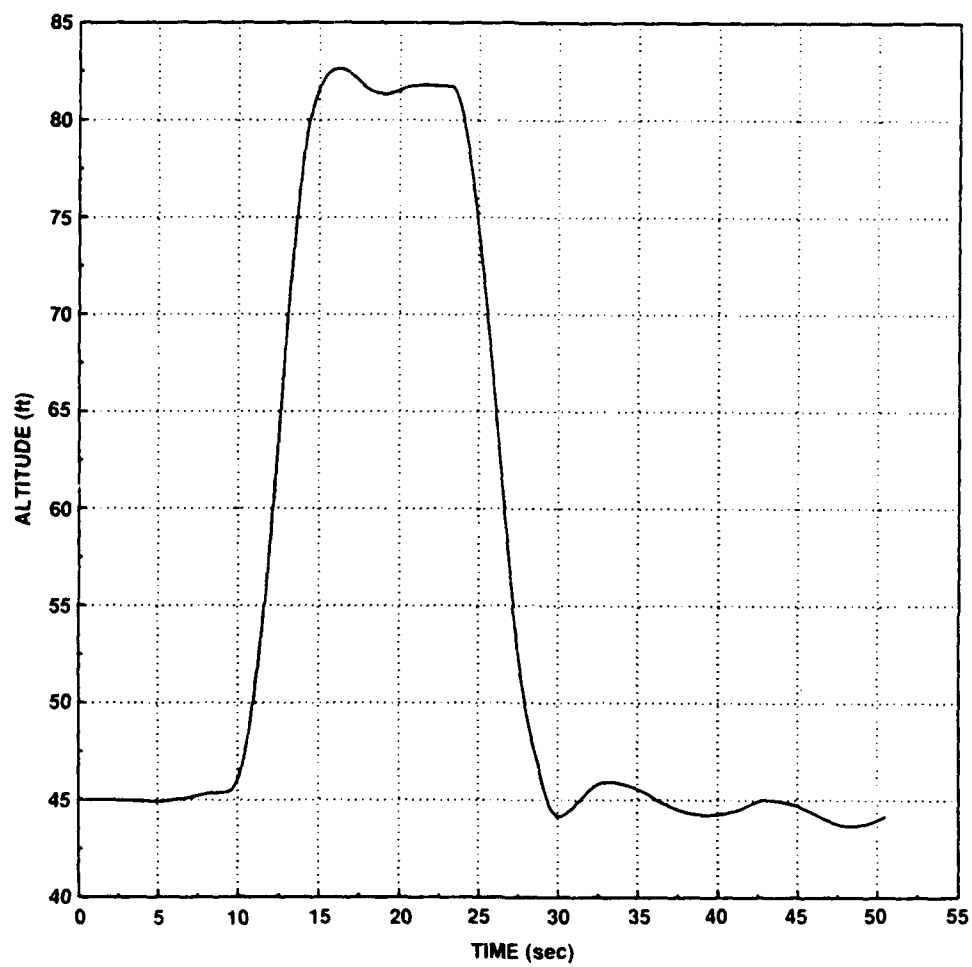
Figure C-7. Bob-up time history data for simulator (Pilot 5).
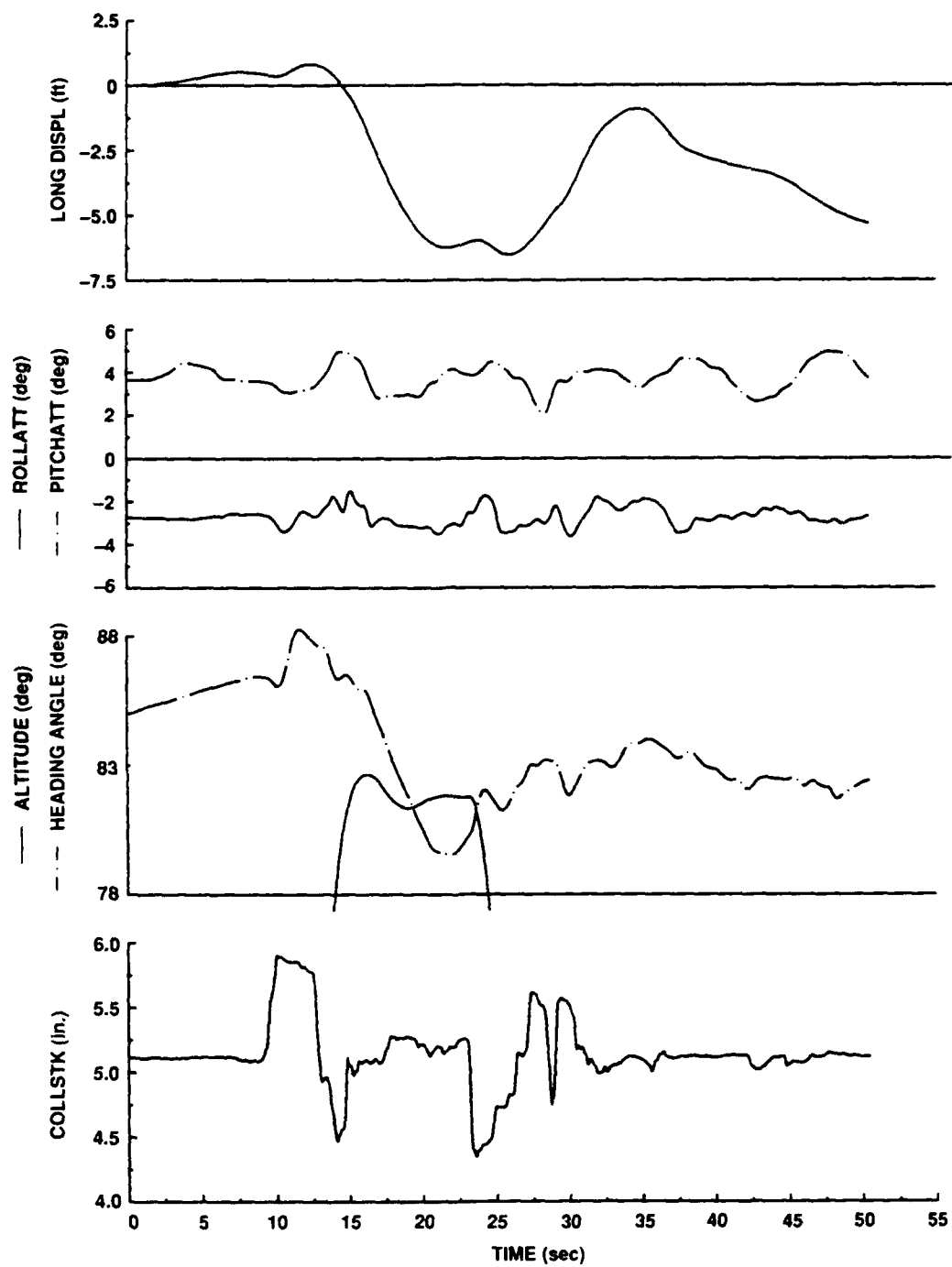
Figure C-7. Bob-up time history data for simulator (Pilot 5) (Continued).
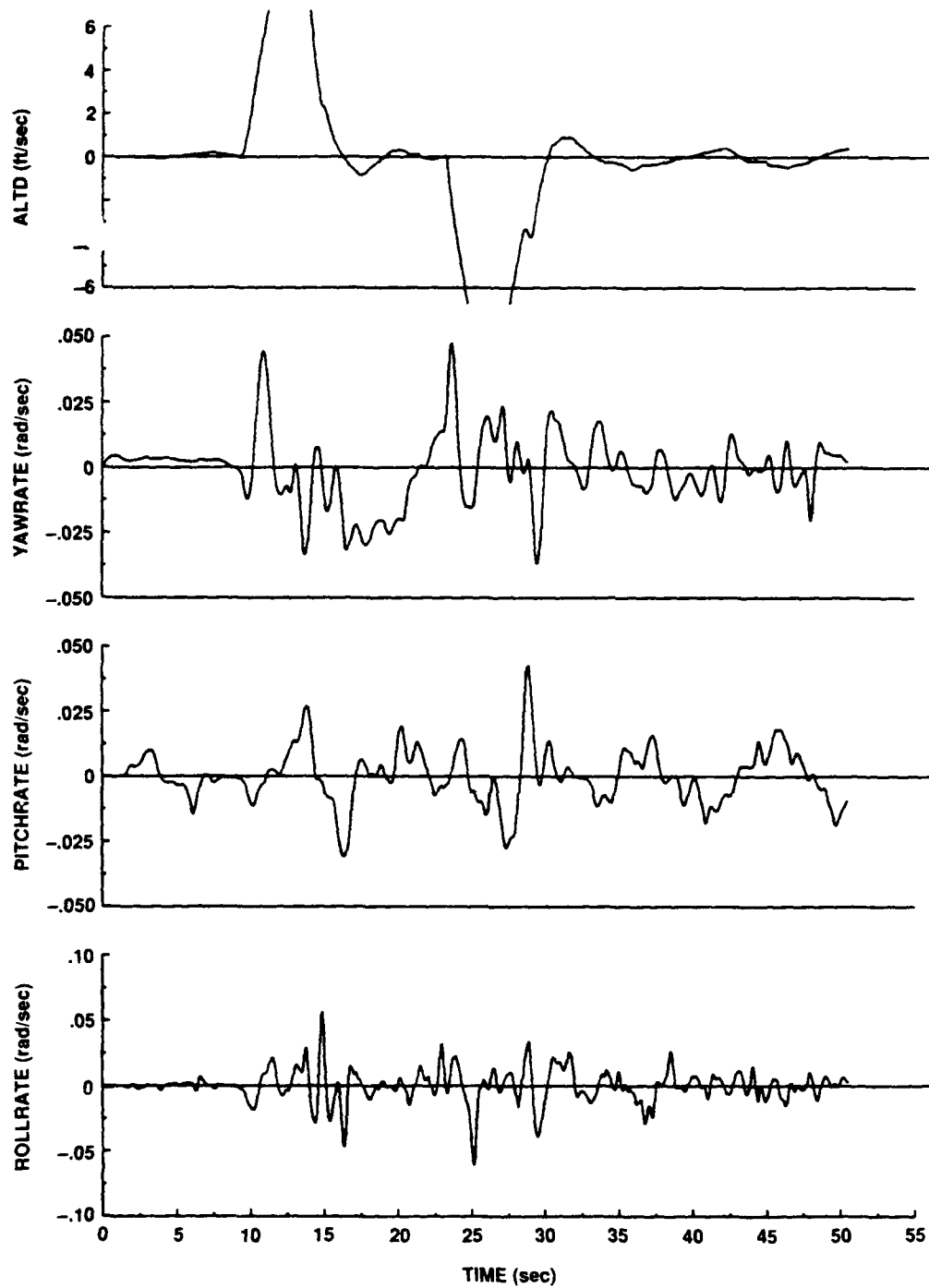
Figure C-7. Bob-up time history data for simulator (Pilot 5) (Continued).

Figure C-7. Bob-up time history data for simulator (Pilot 5) (Continued).
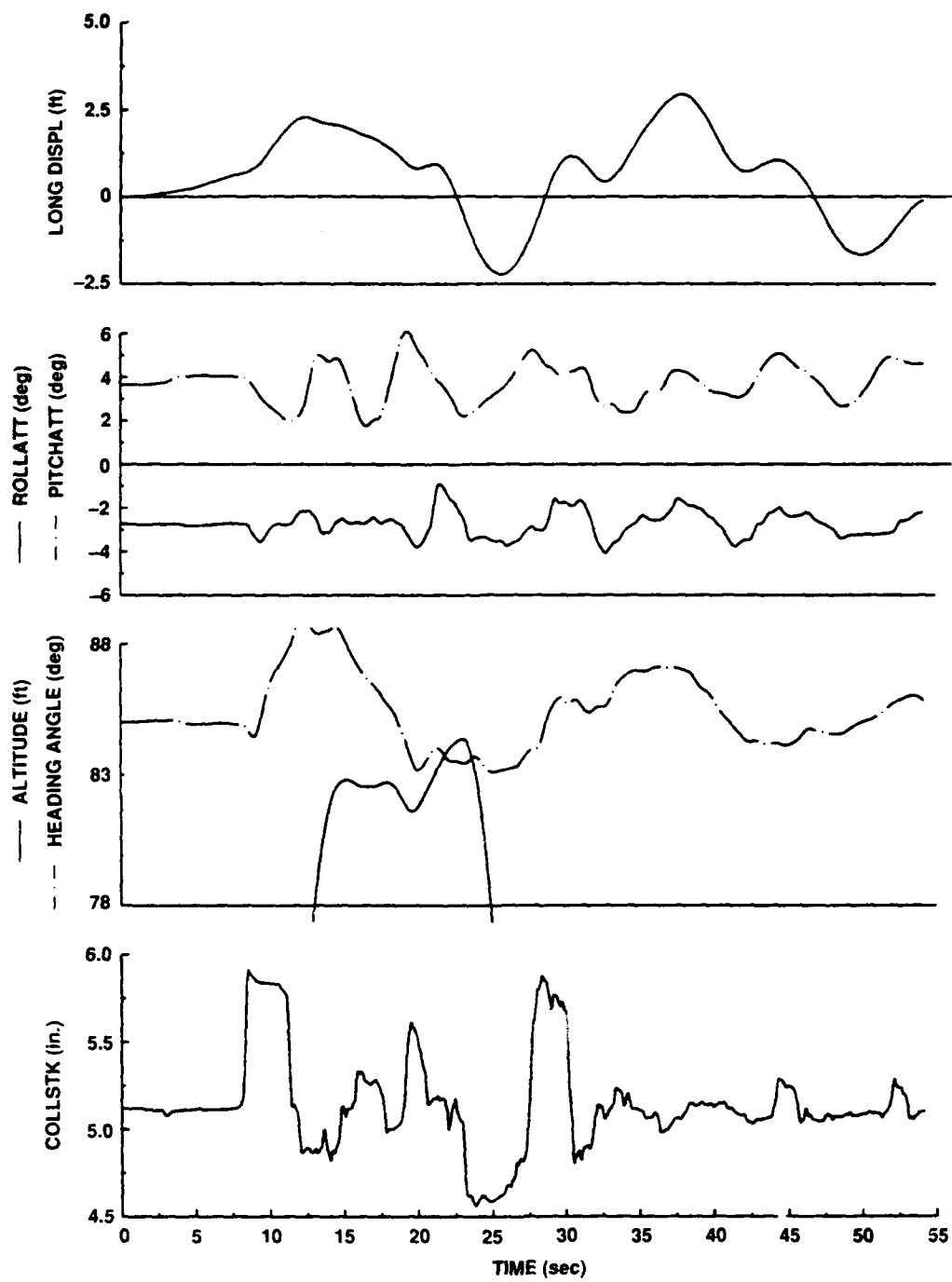
Figure C-7. Bob-up time history data for simulator (Pilot 5) (Continued).
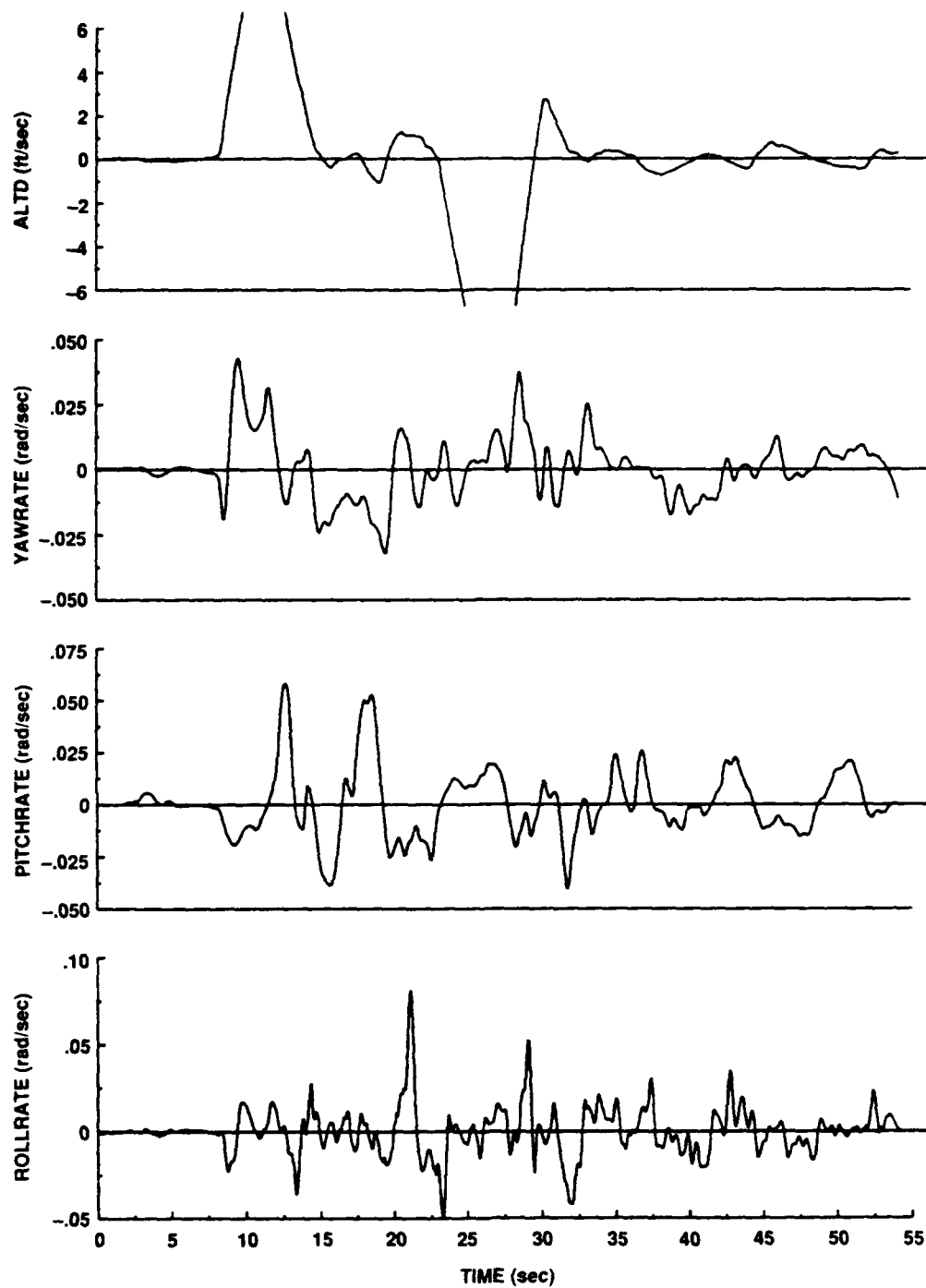
Figure C-7. Bob-up time history data for simulator (Pilot 5) (Continued).
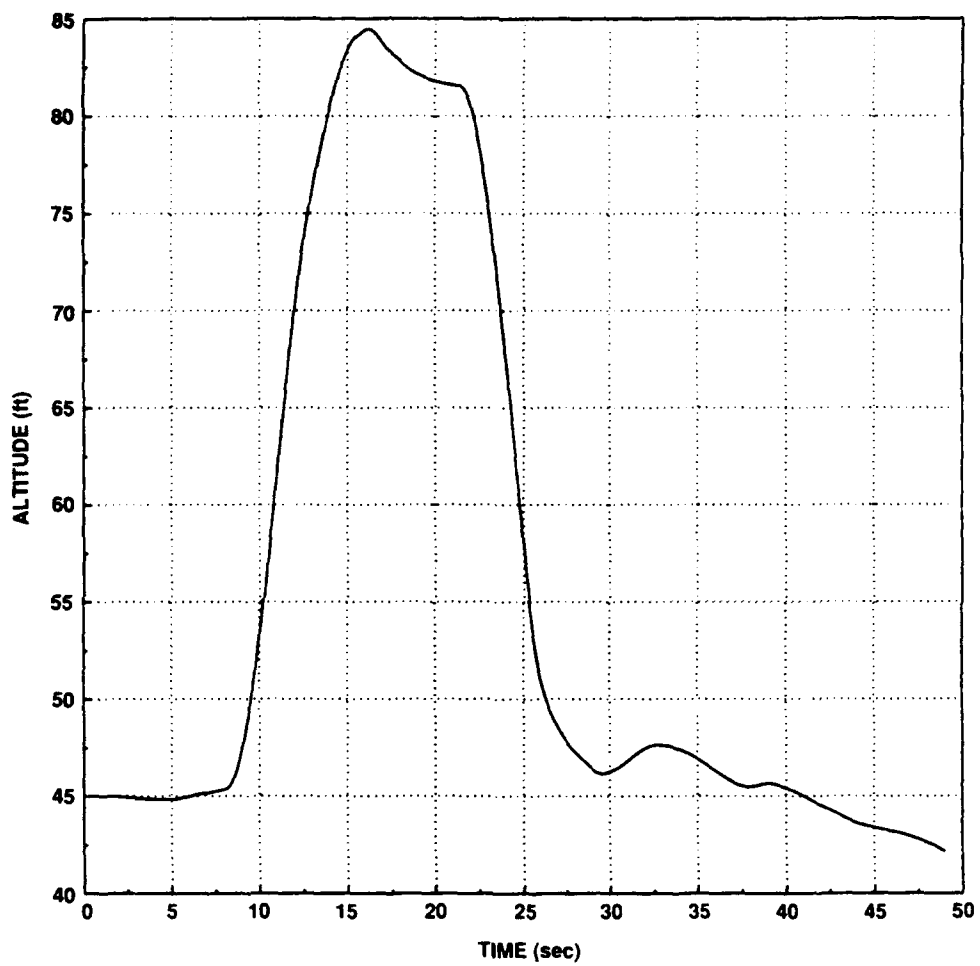
Figure C-7. Bob-up time history data for simulator (Pilot 5) (Continued).

Figure C-7. Bob-up time history data for simulator (Pilot 5) (Continued).
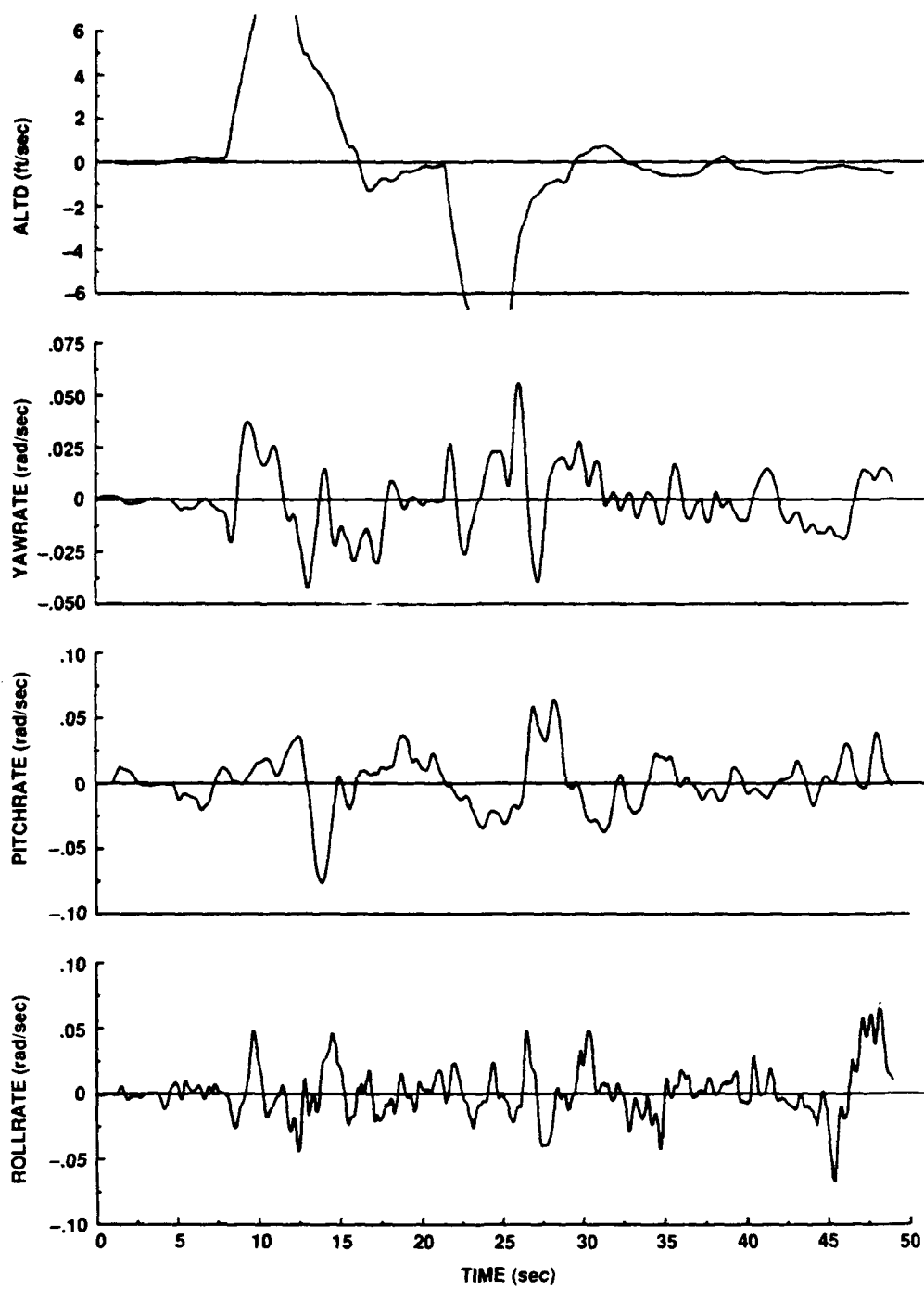
Figure C-7. Bob-up time history data for simulator (Pilot 5) (Concluded).
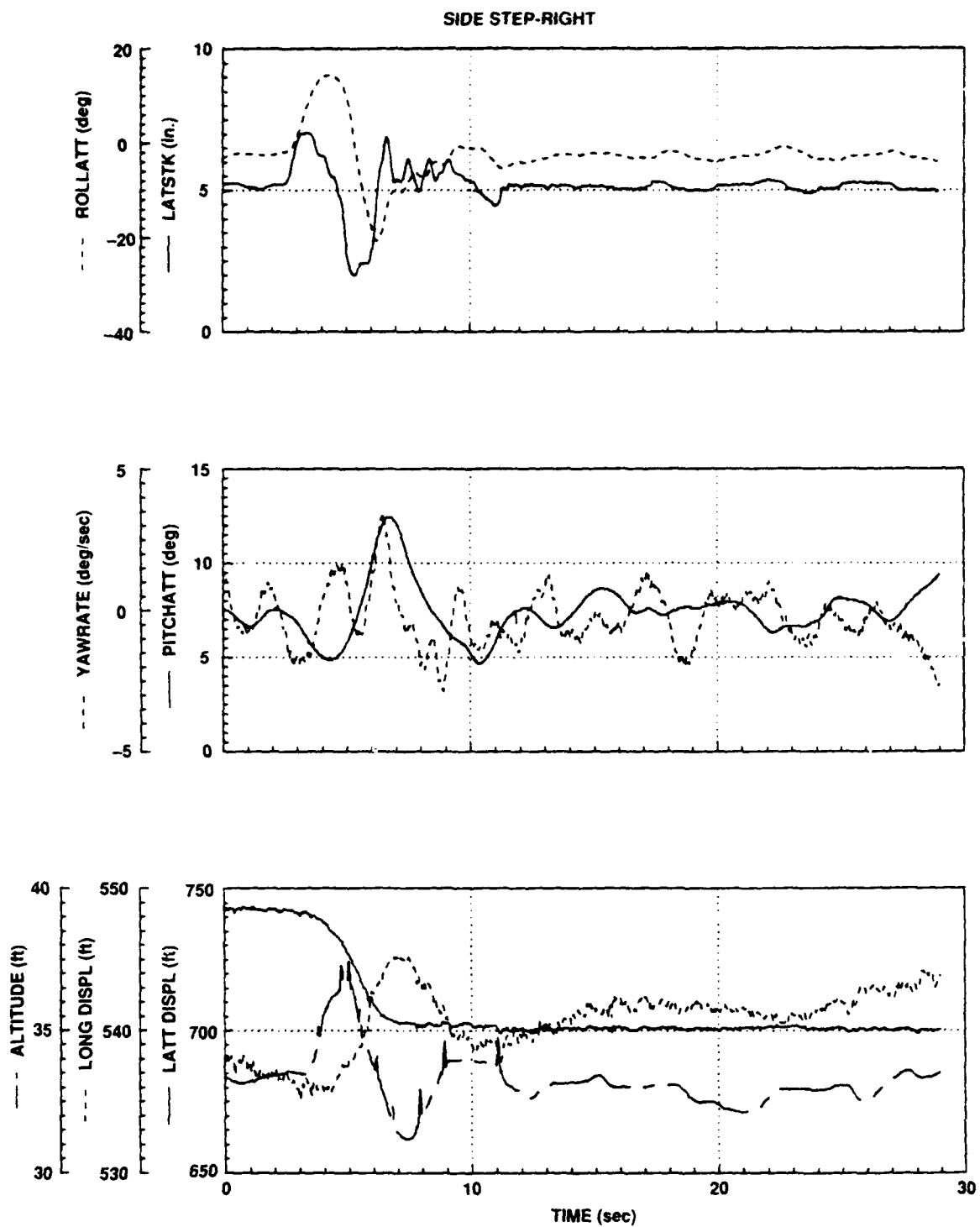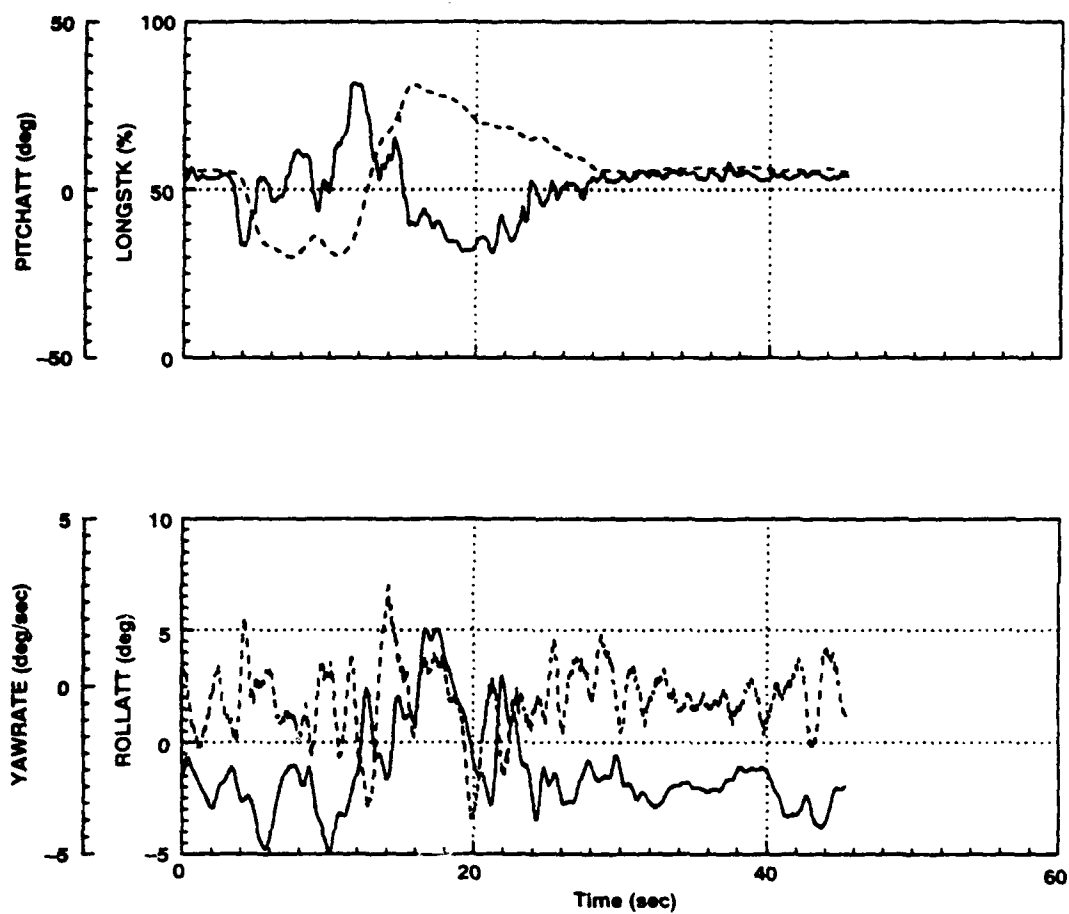
Figure C-8. Side-step time history data for flight (Pilot 1).
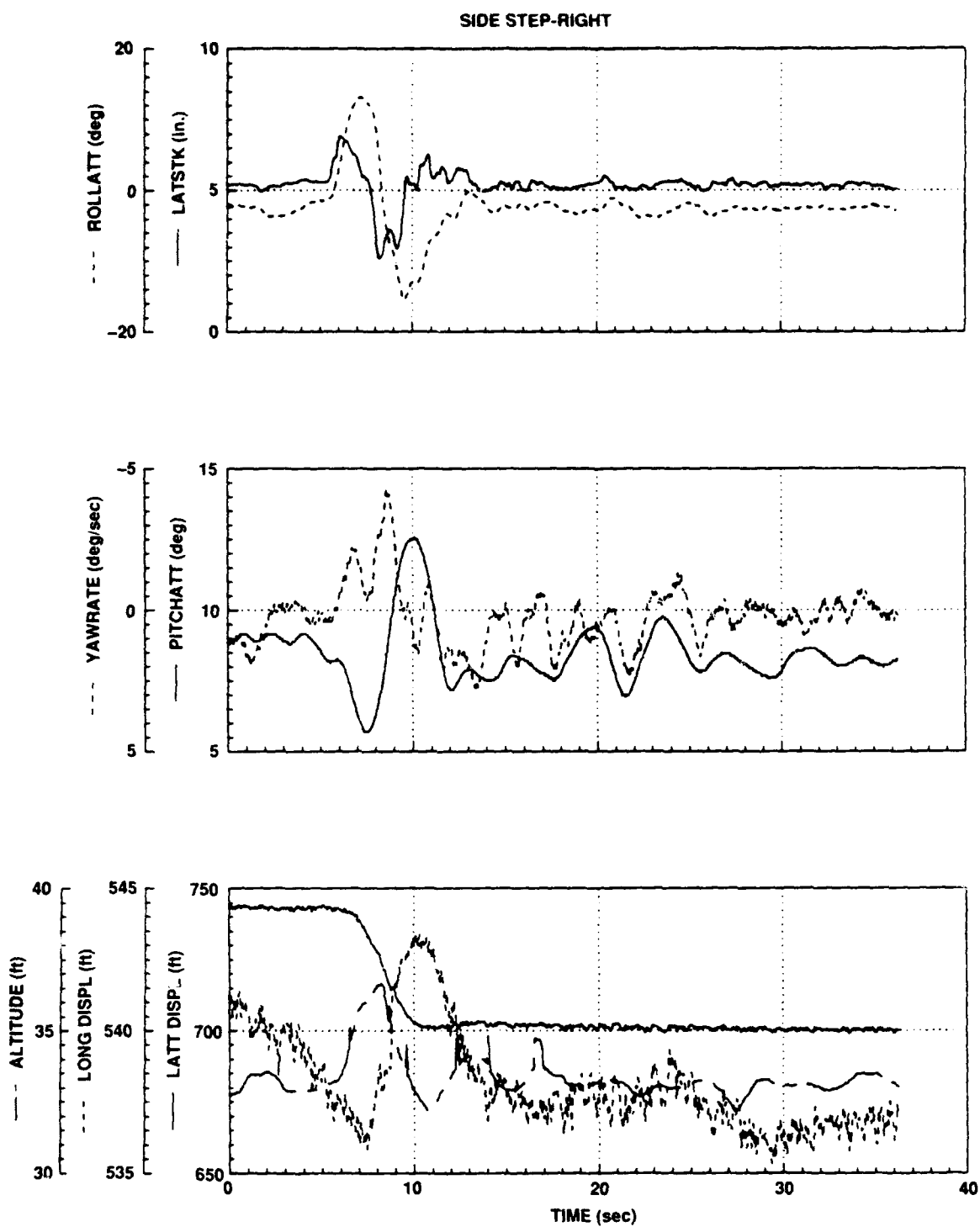
Figure C-8. Side-step time history data for flight (Pilot 1) (Continued).
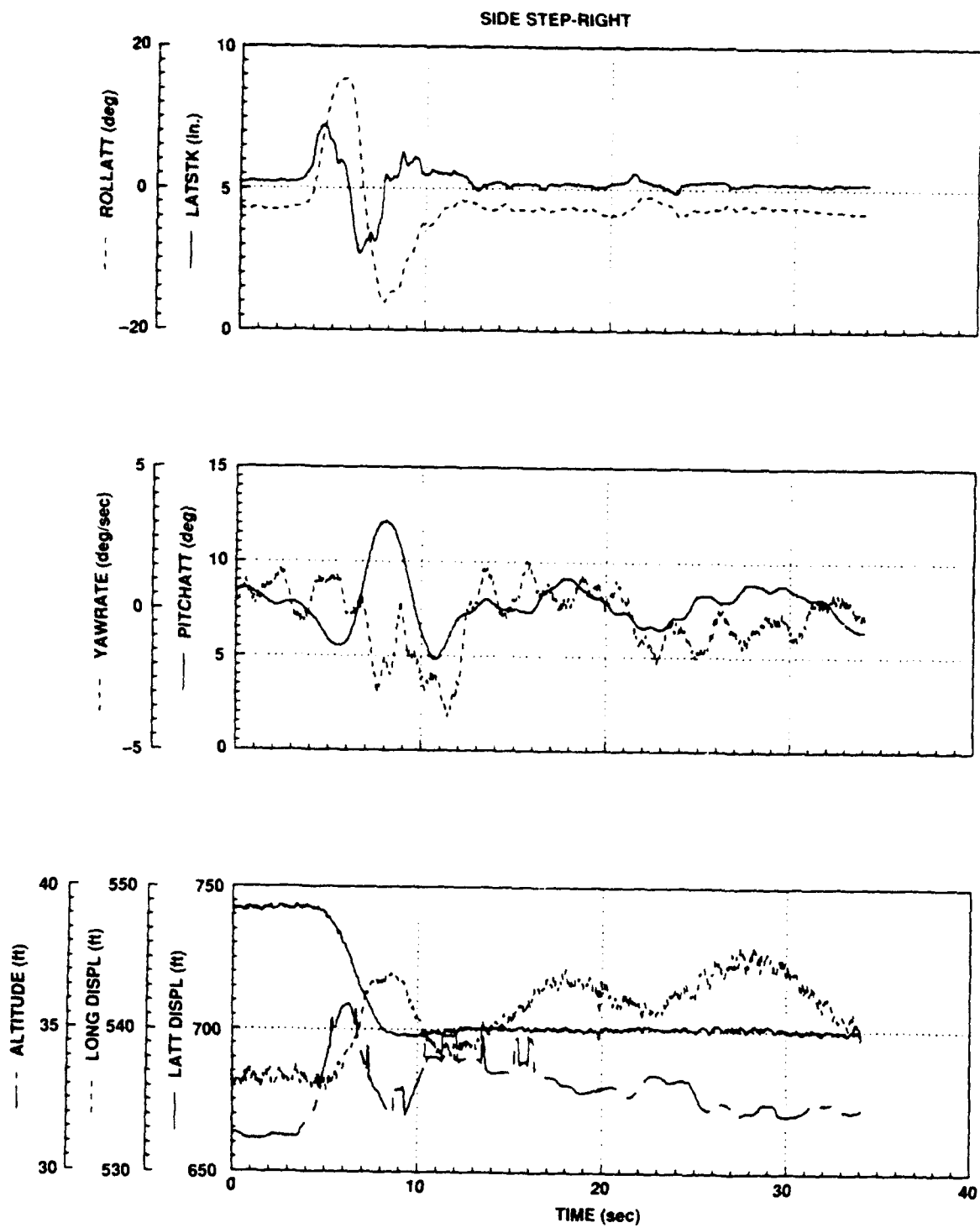
Figure C-8. Side-step time history data for flight (Pilot 1) (Continued).
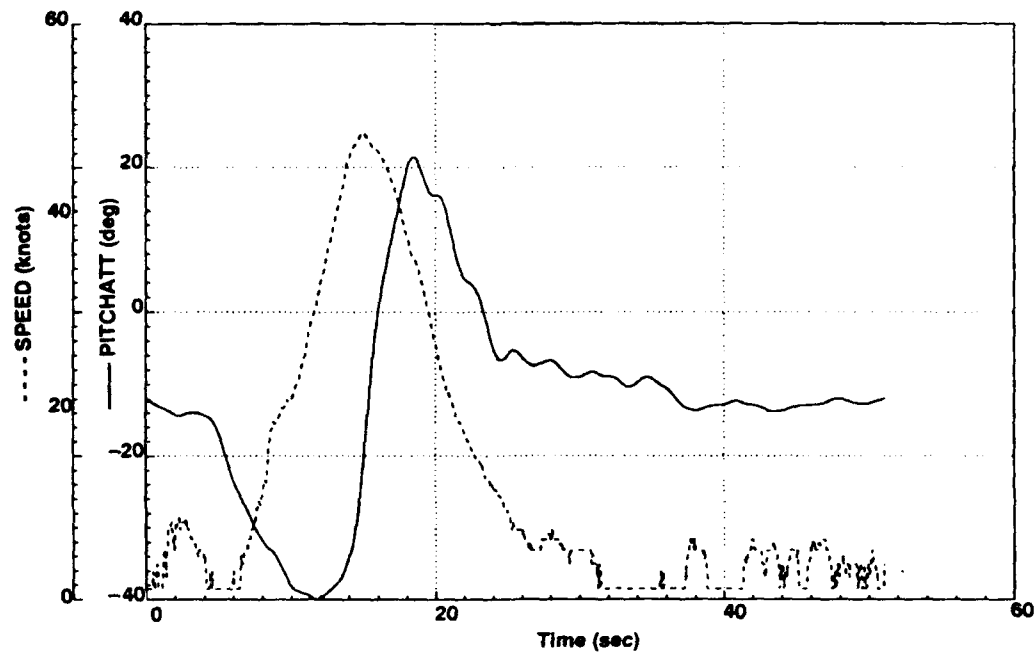
Figure C-8. Side-step time history data for flight (Pilot 1) (Continued).

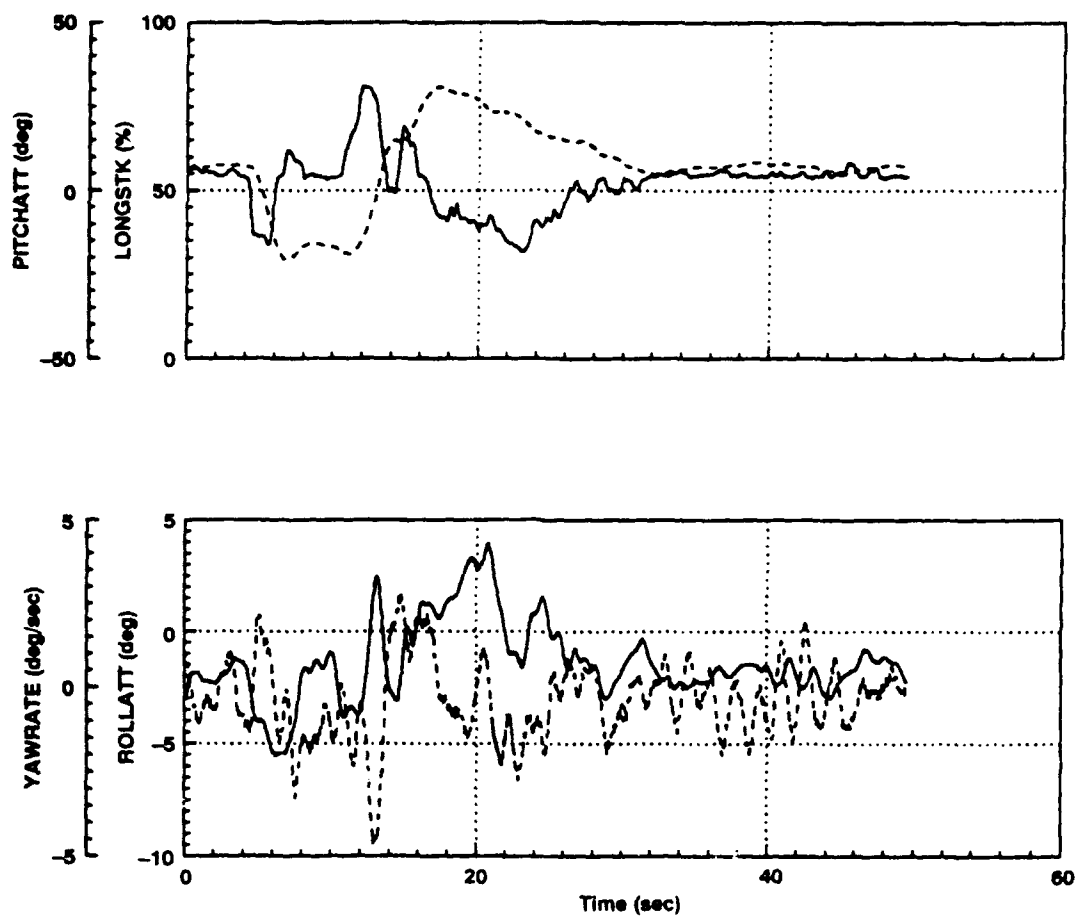Figure C-8. Side-step time history data for flight (Pilot 1) (Continued).

216

Figure C-8. Side-step time history data for flight (Pilot 1) (Continued).

217

SIDE STEP-RIGHT-AGGRESSIVE
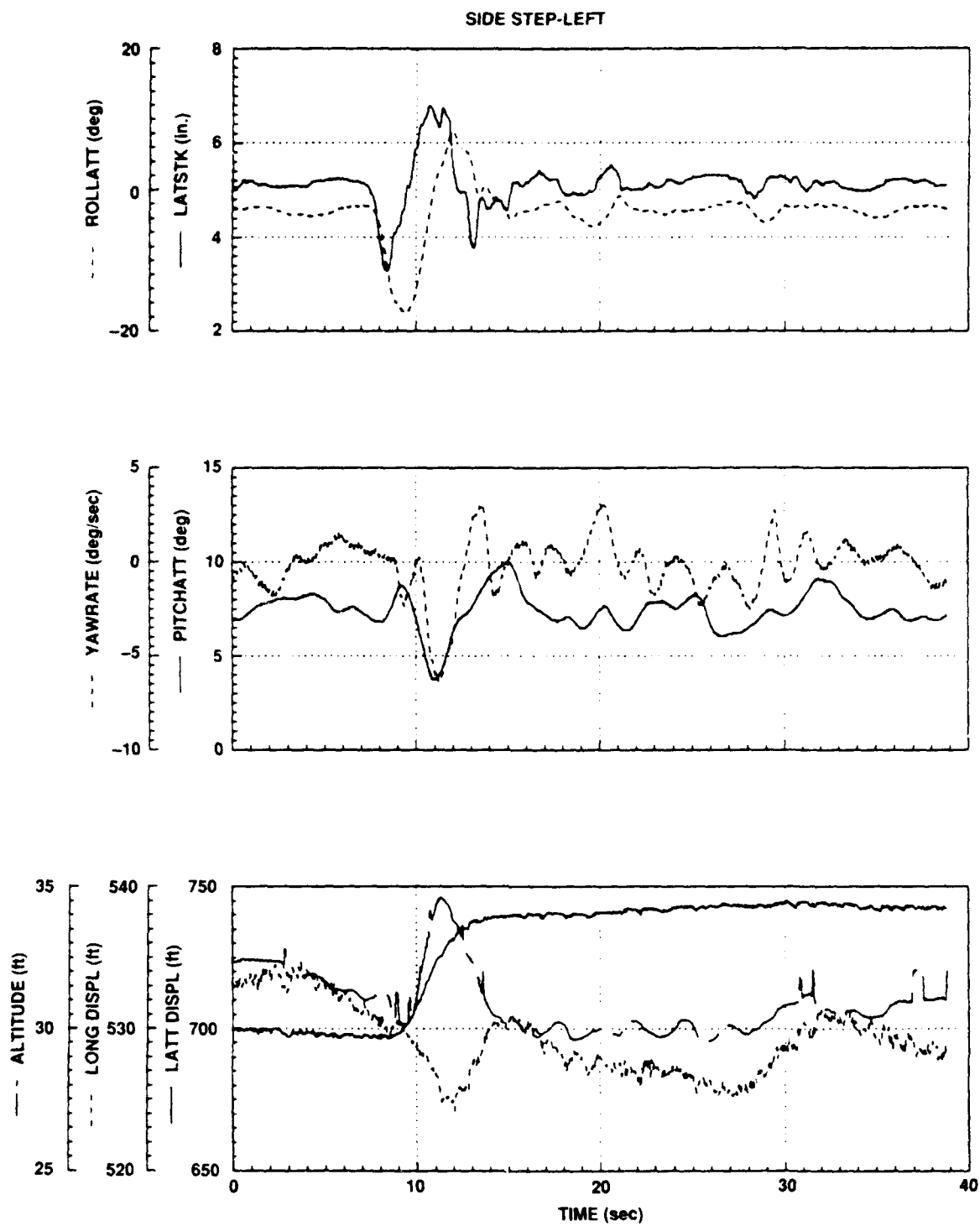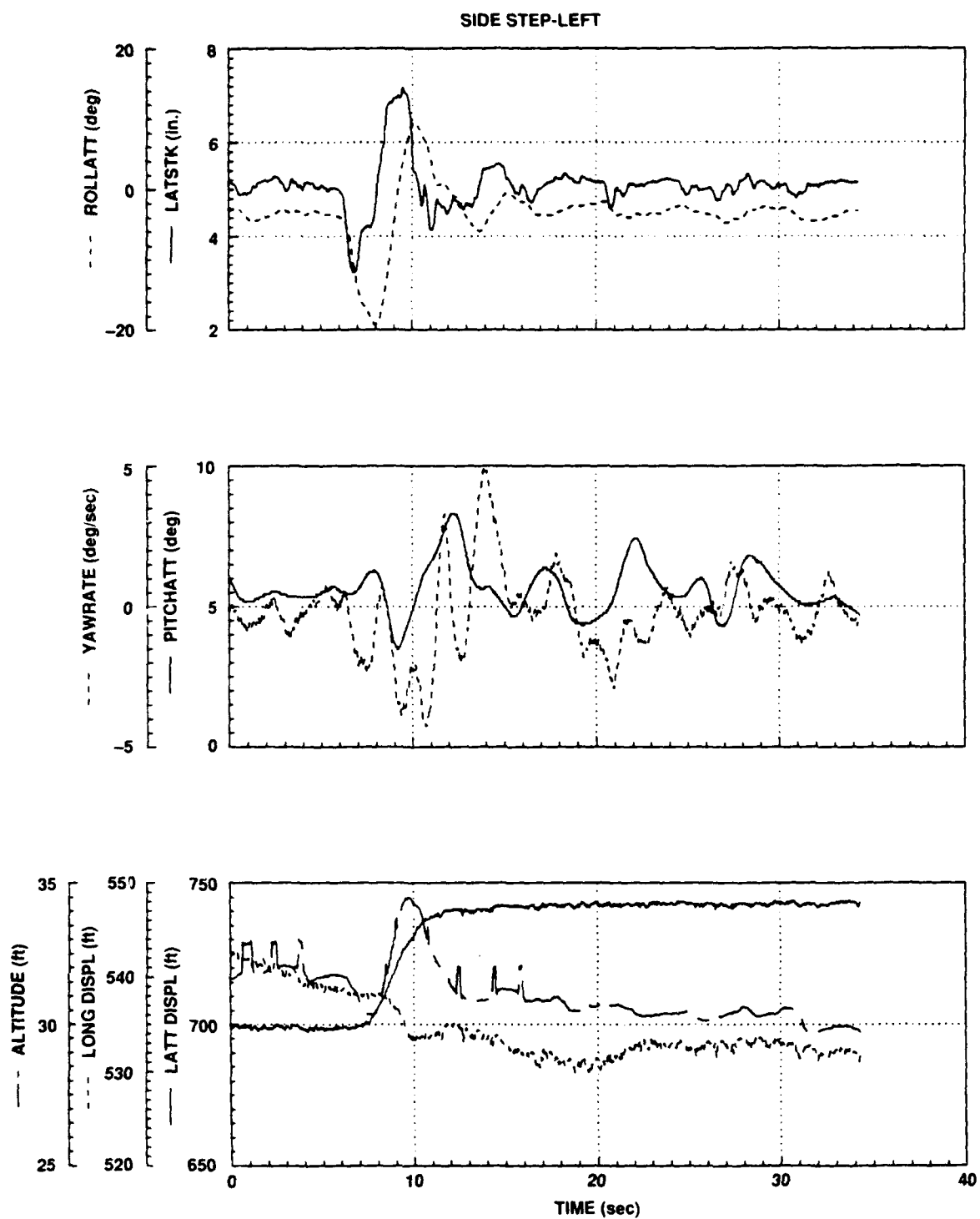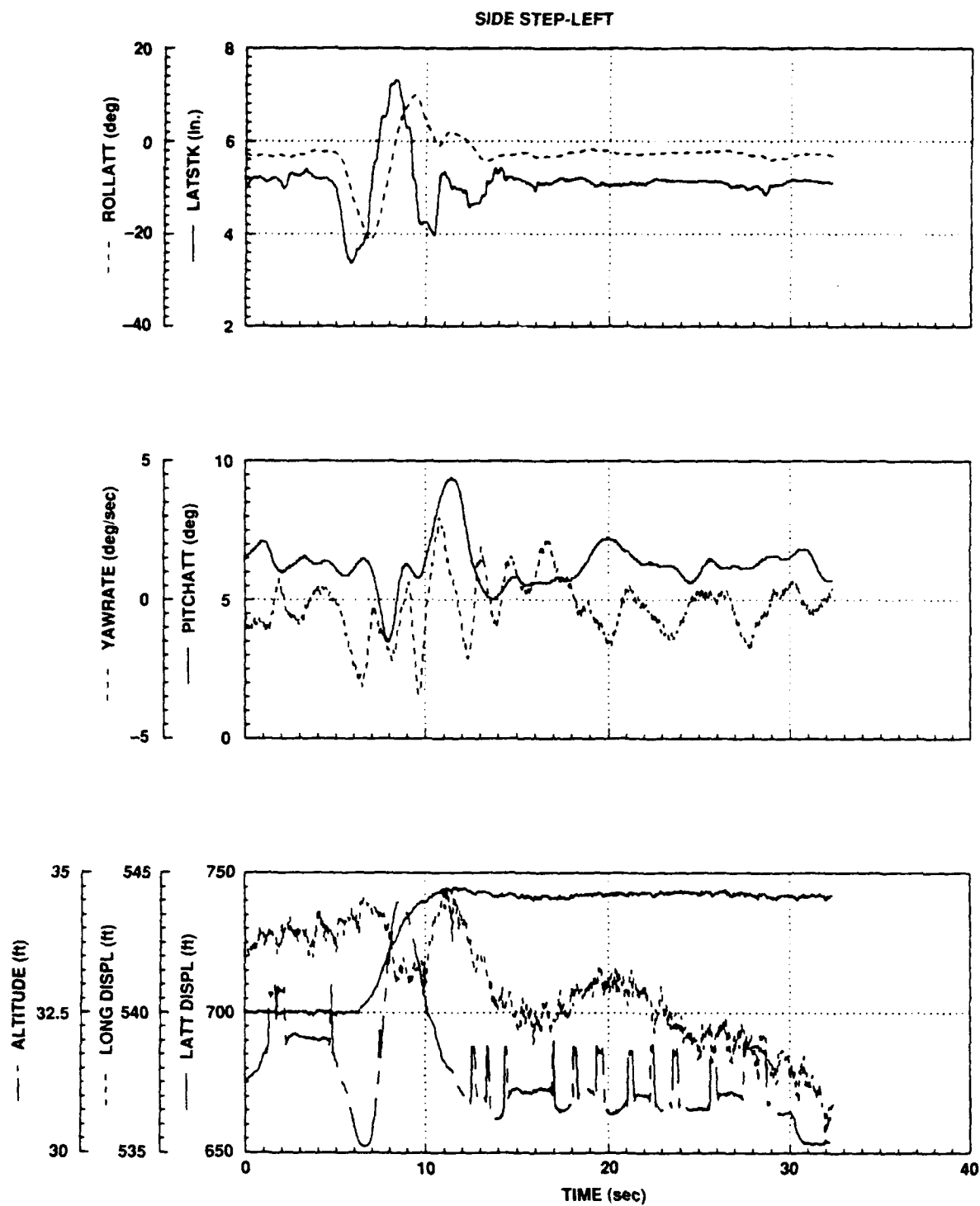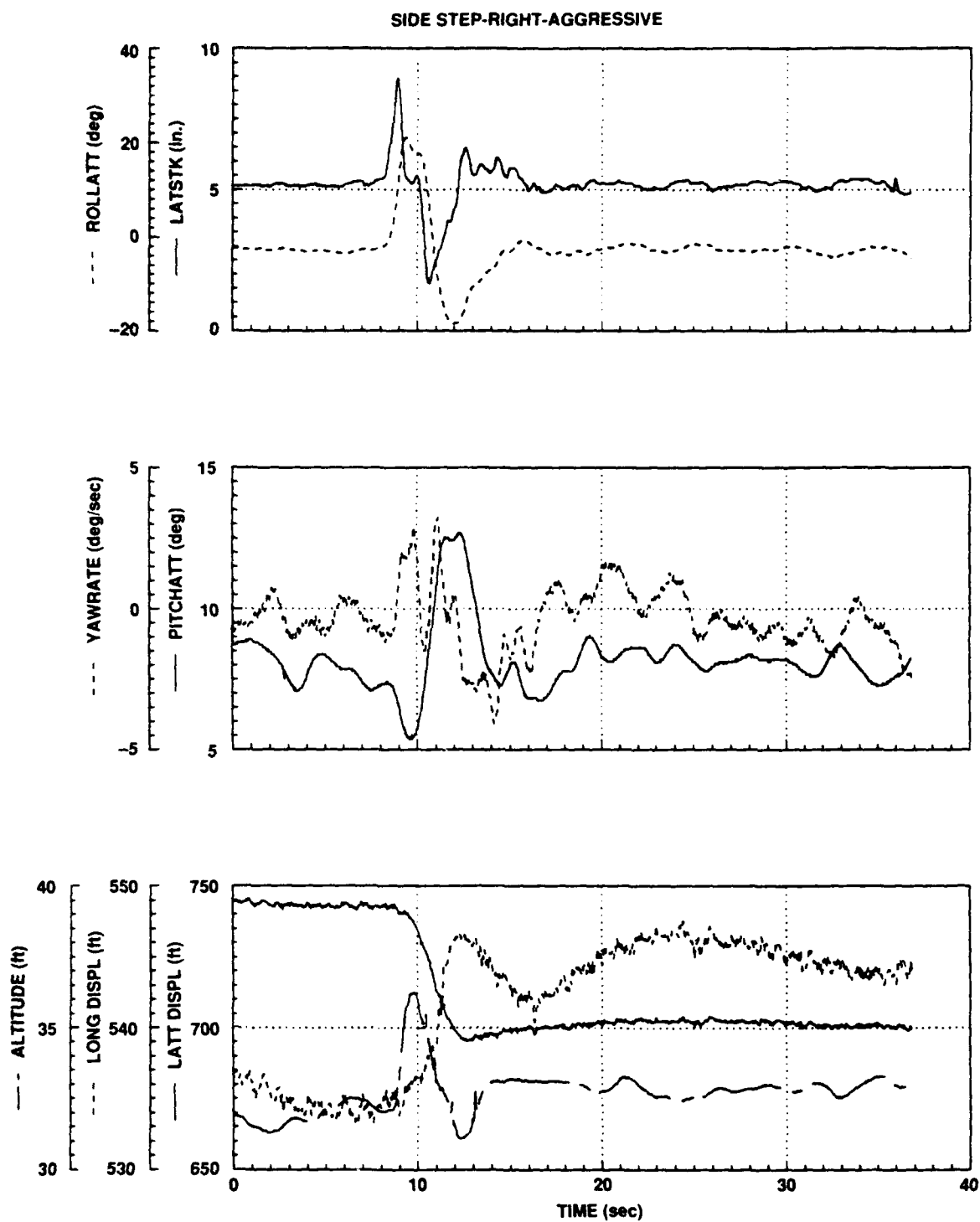
Figure C-8. Side-step time history data for flight (Pilot 1) (Concluded).
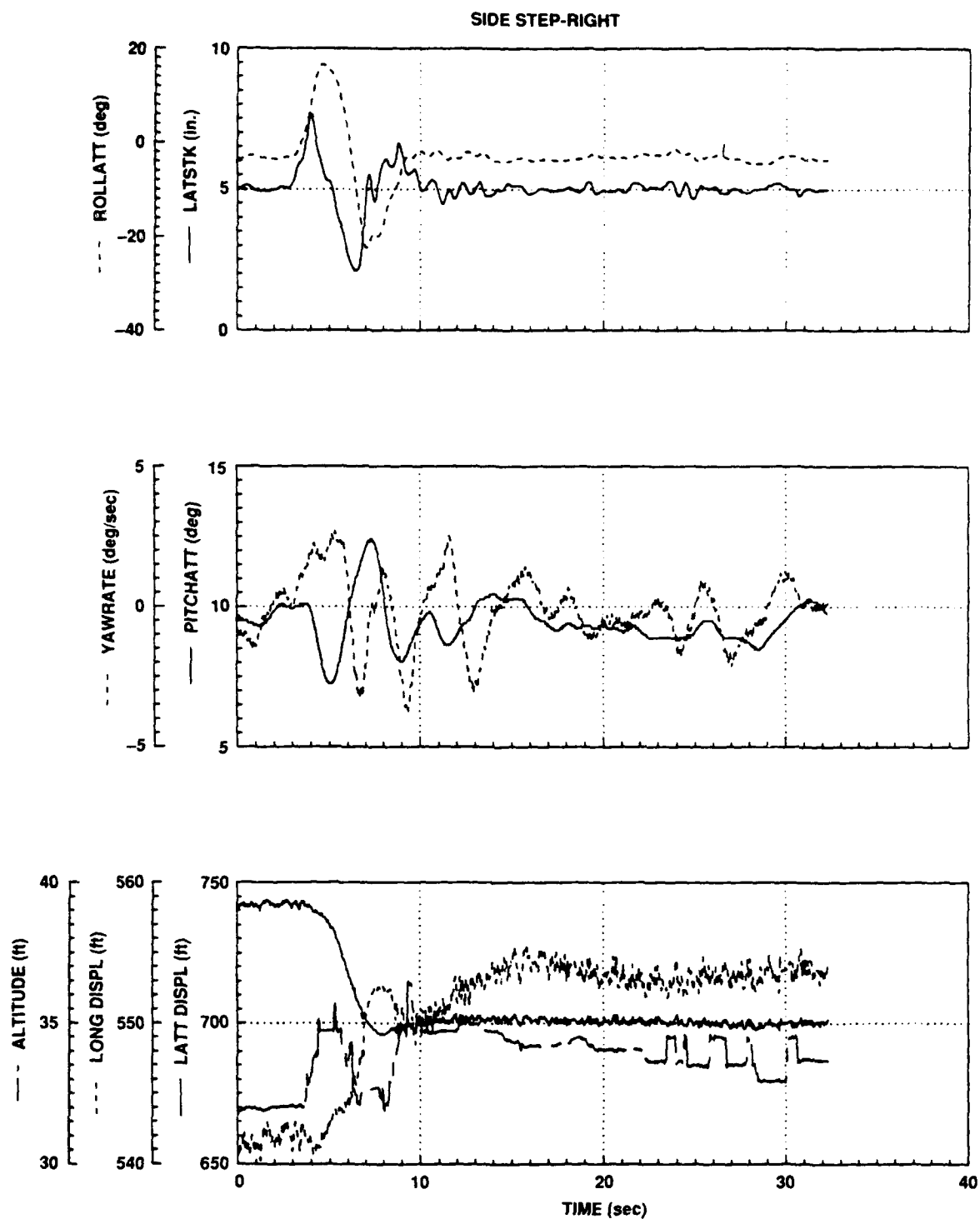
Figure C-9. Side-step time history data for flight (Pilot 2).
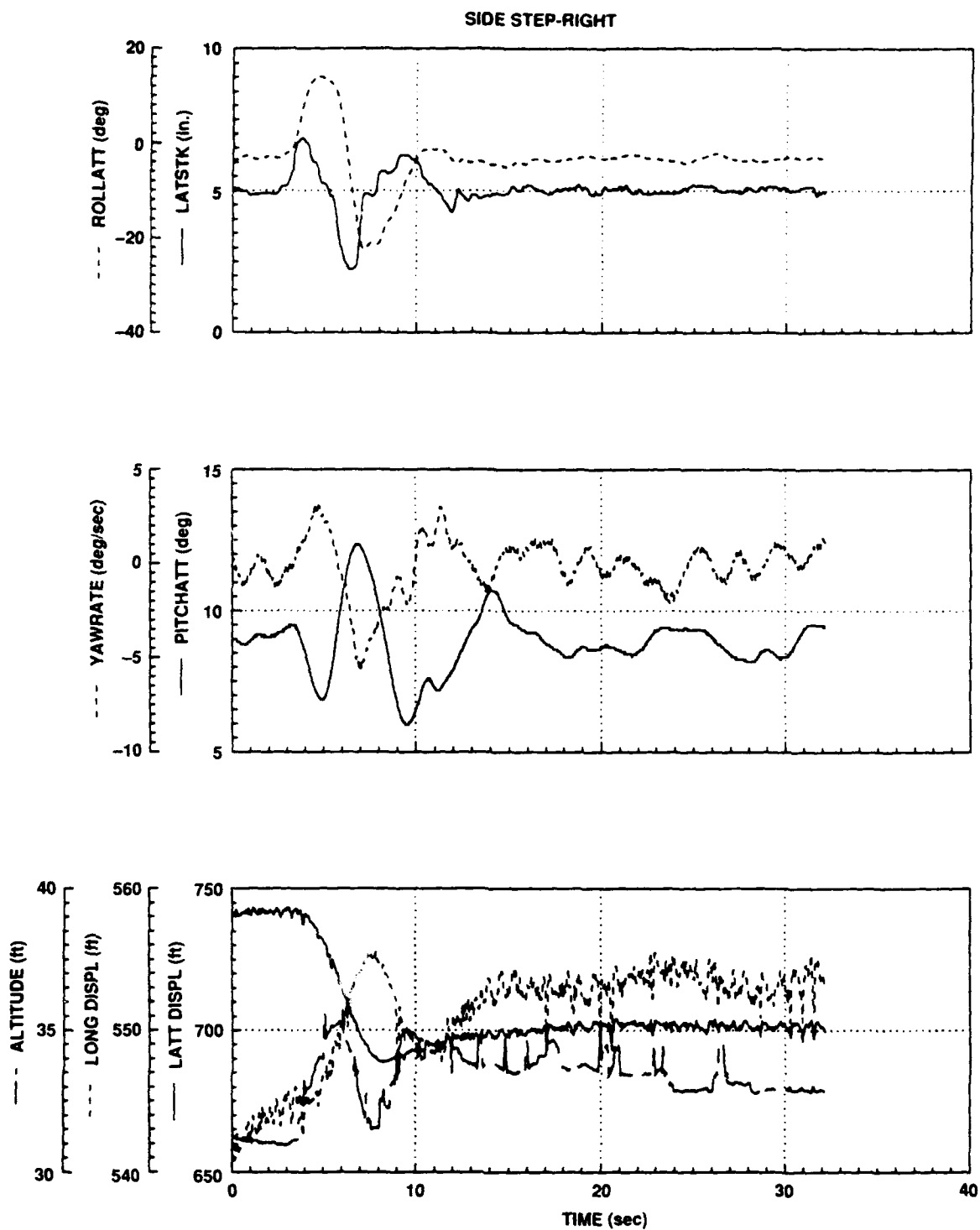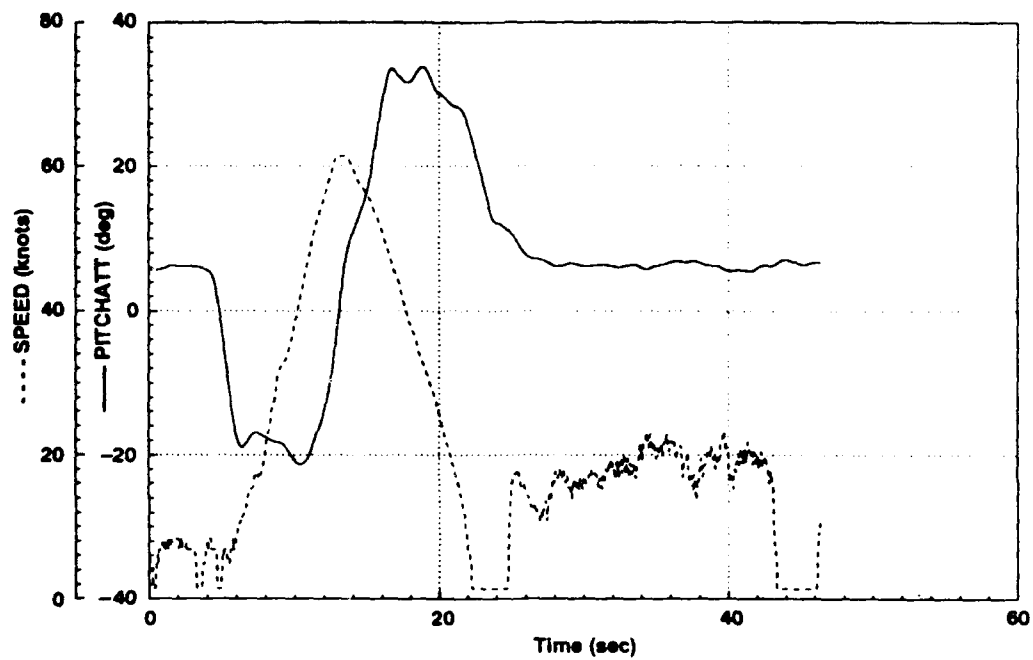
Figure C-9. Side-step time history data for flight (Pilot 2) (Continued).
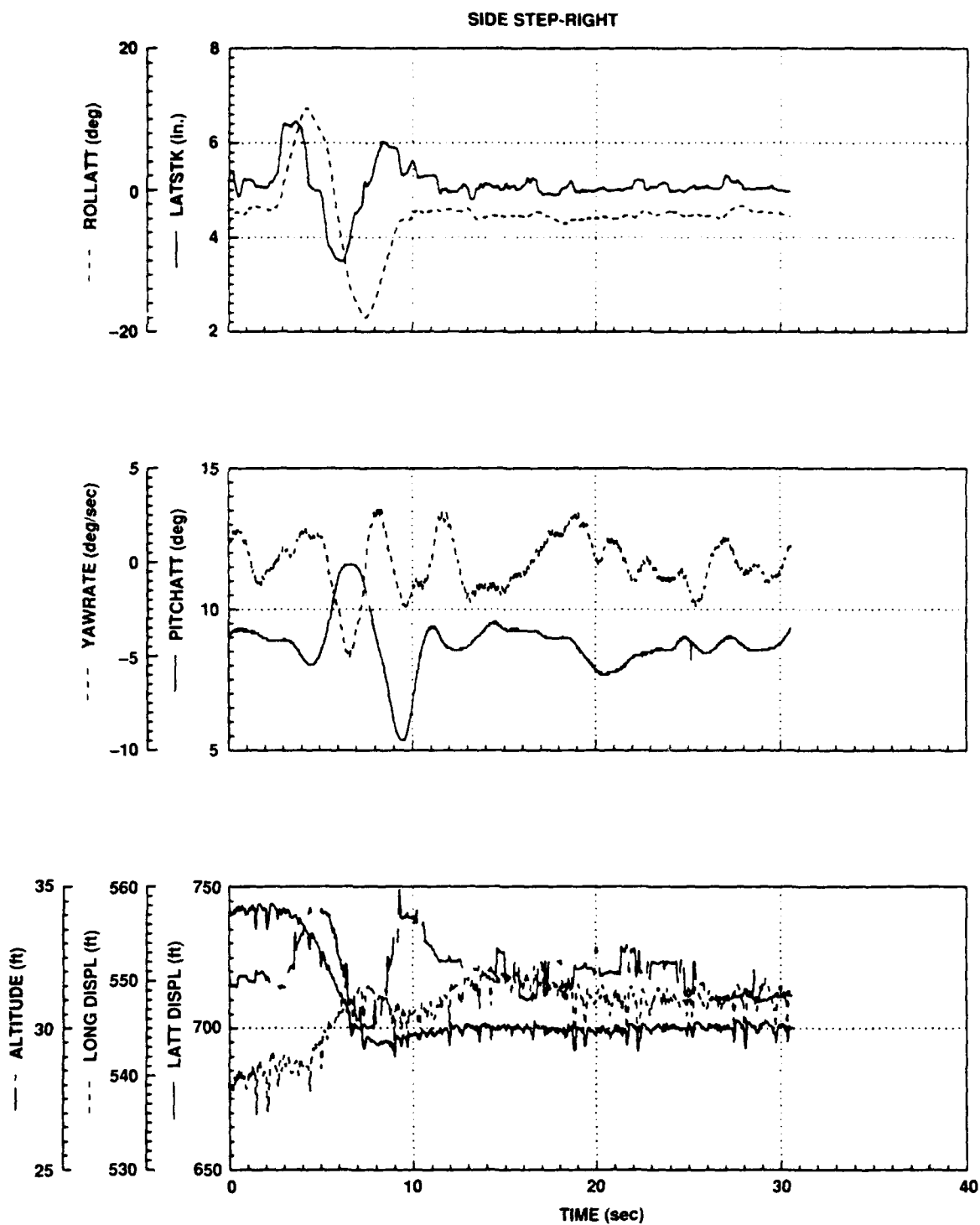
Figure C-9. Side-step time history data for flight (Pilot 2) (Continued).
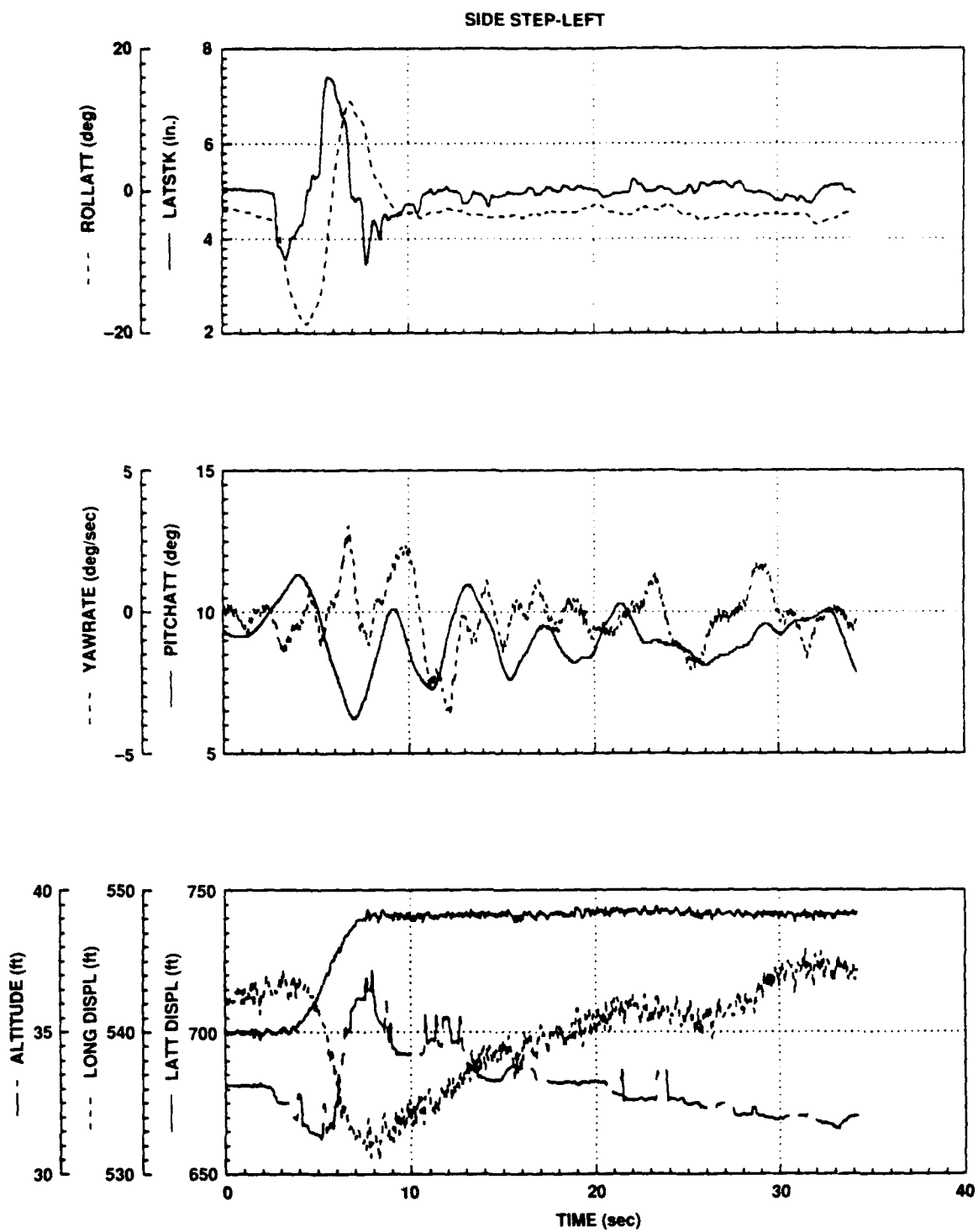
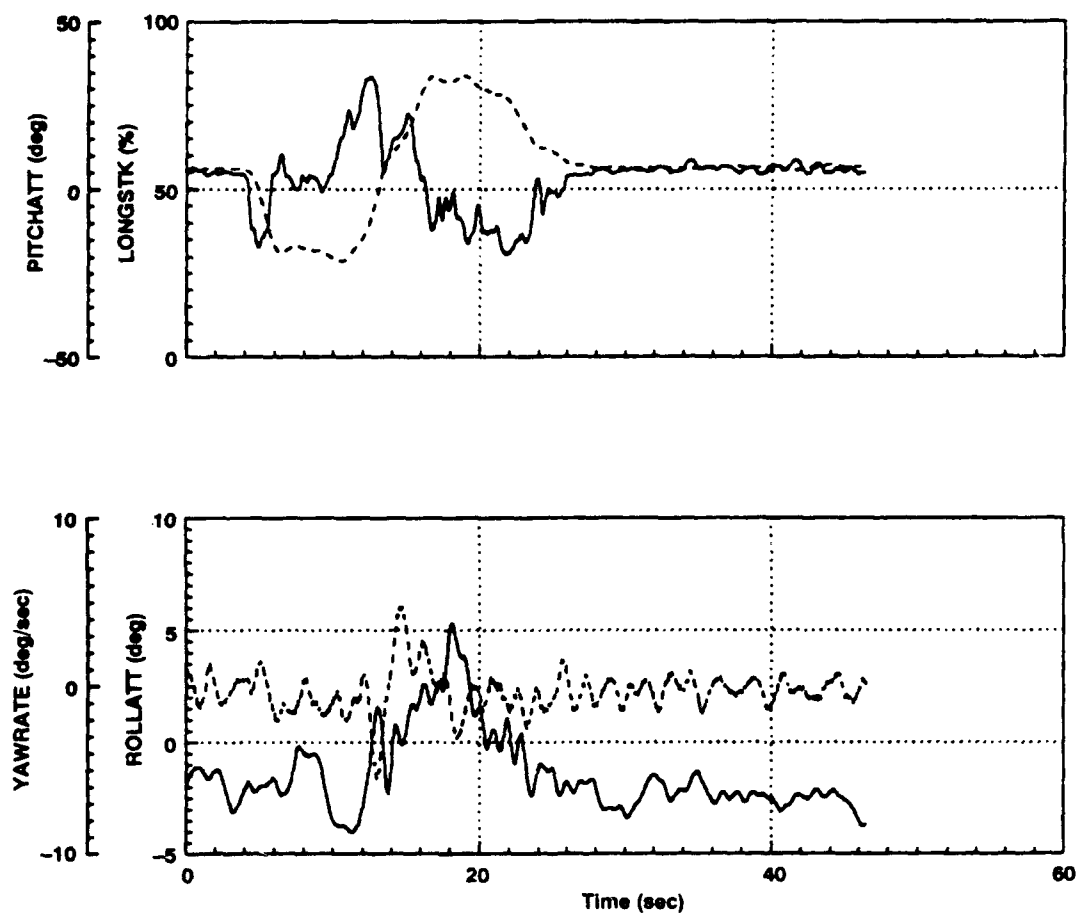Figure C-9. Side-step time history data for flight (Pilot 2) (Continued).
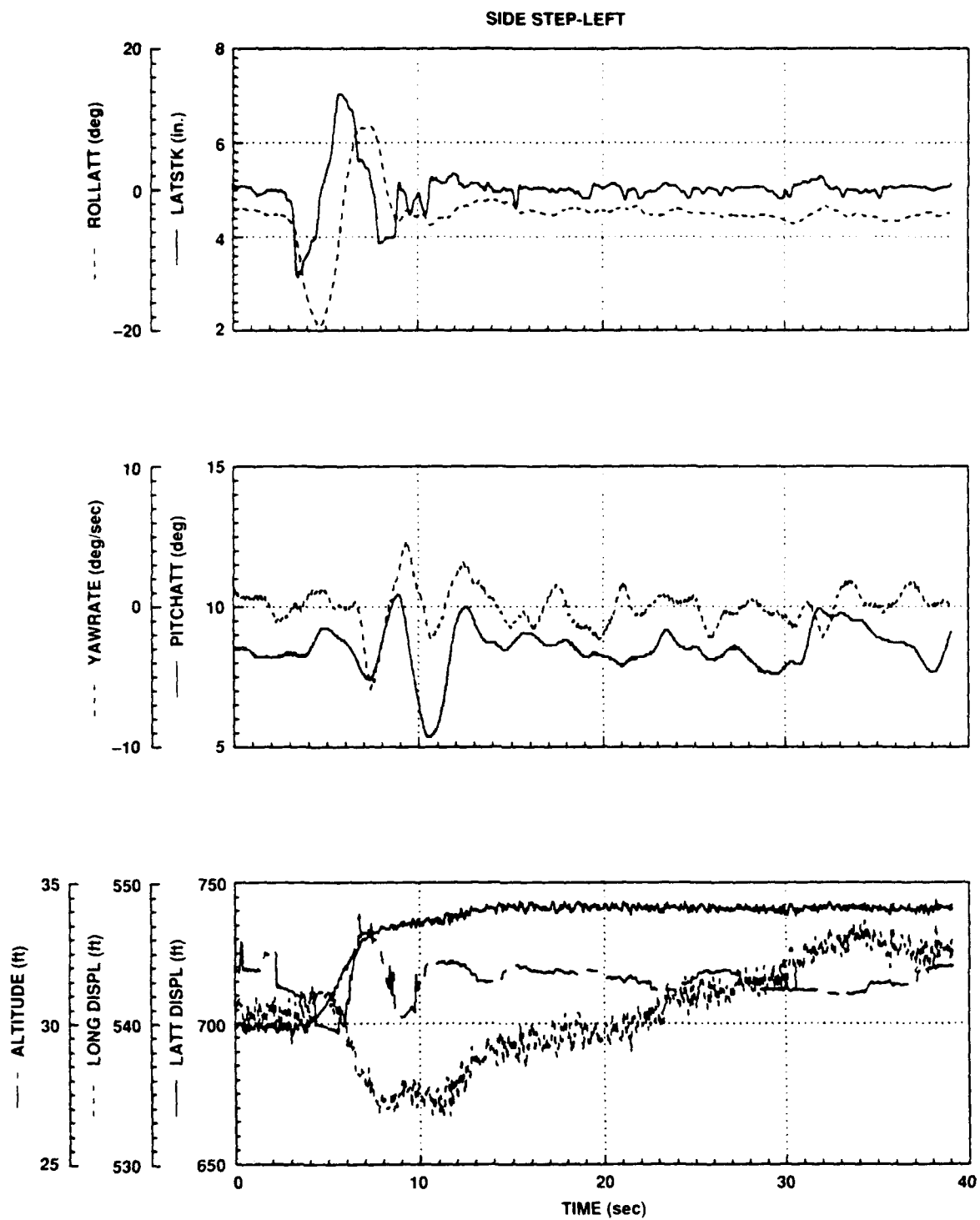
Figure C-9. Side-step time history data for flight (Pilot 2) (Continued).
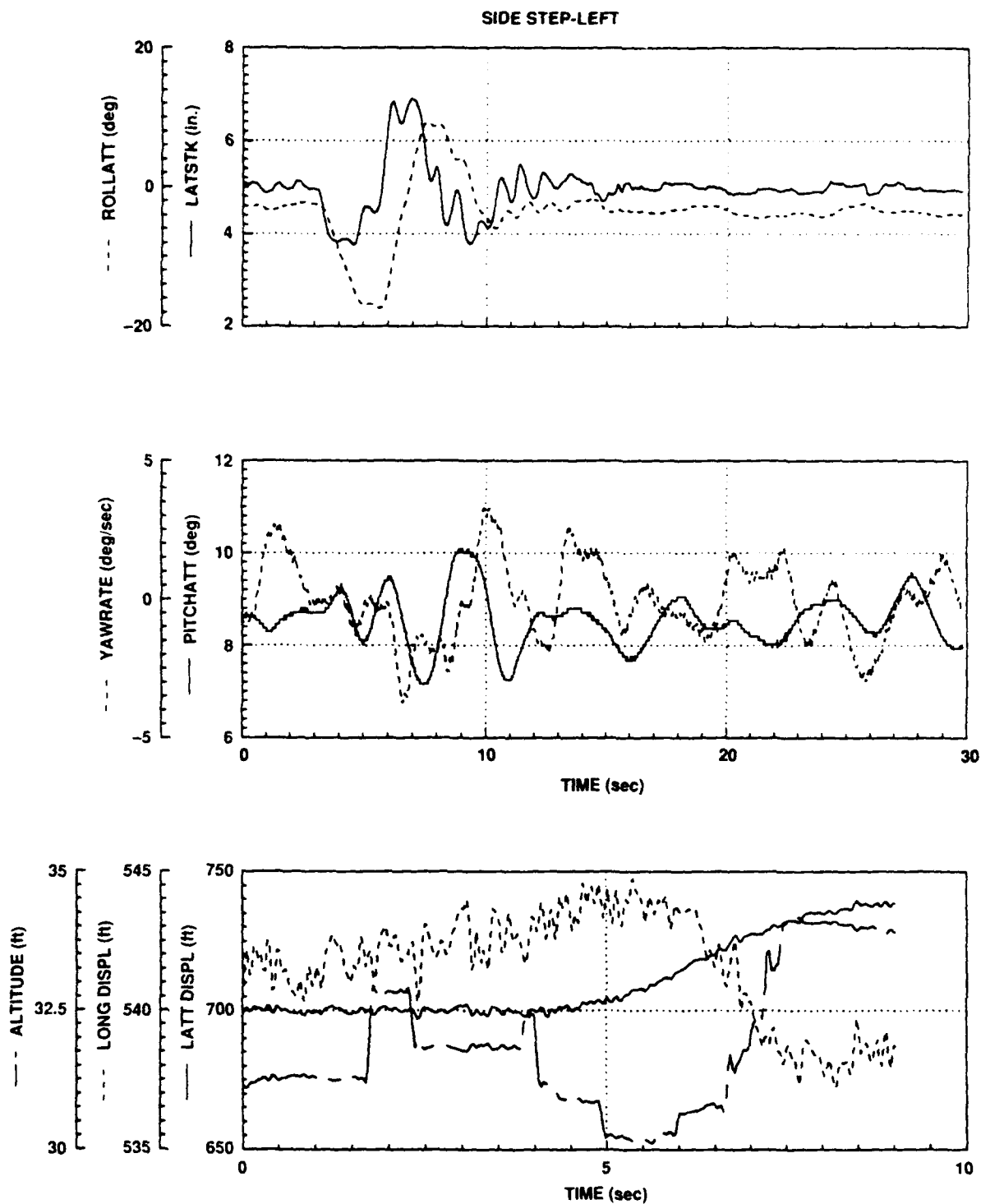
Figure C-9. Side-step time history data for flight (Pilot 2) (Concluded).
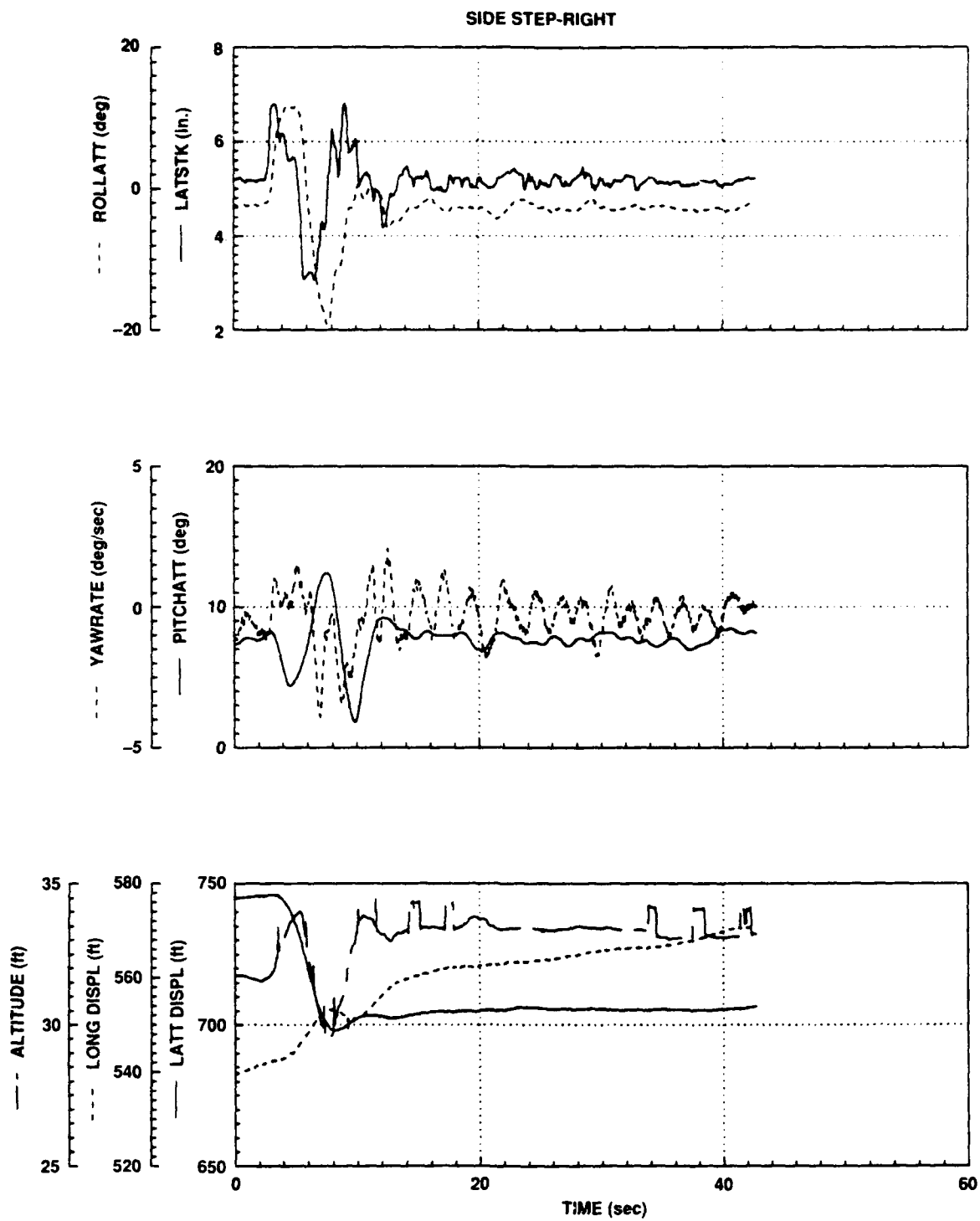
Figure C-10. Side-step time history data for flight (Pilot 3).
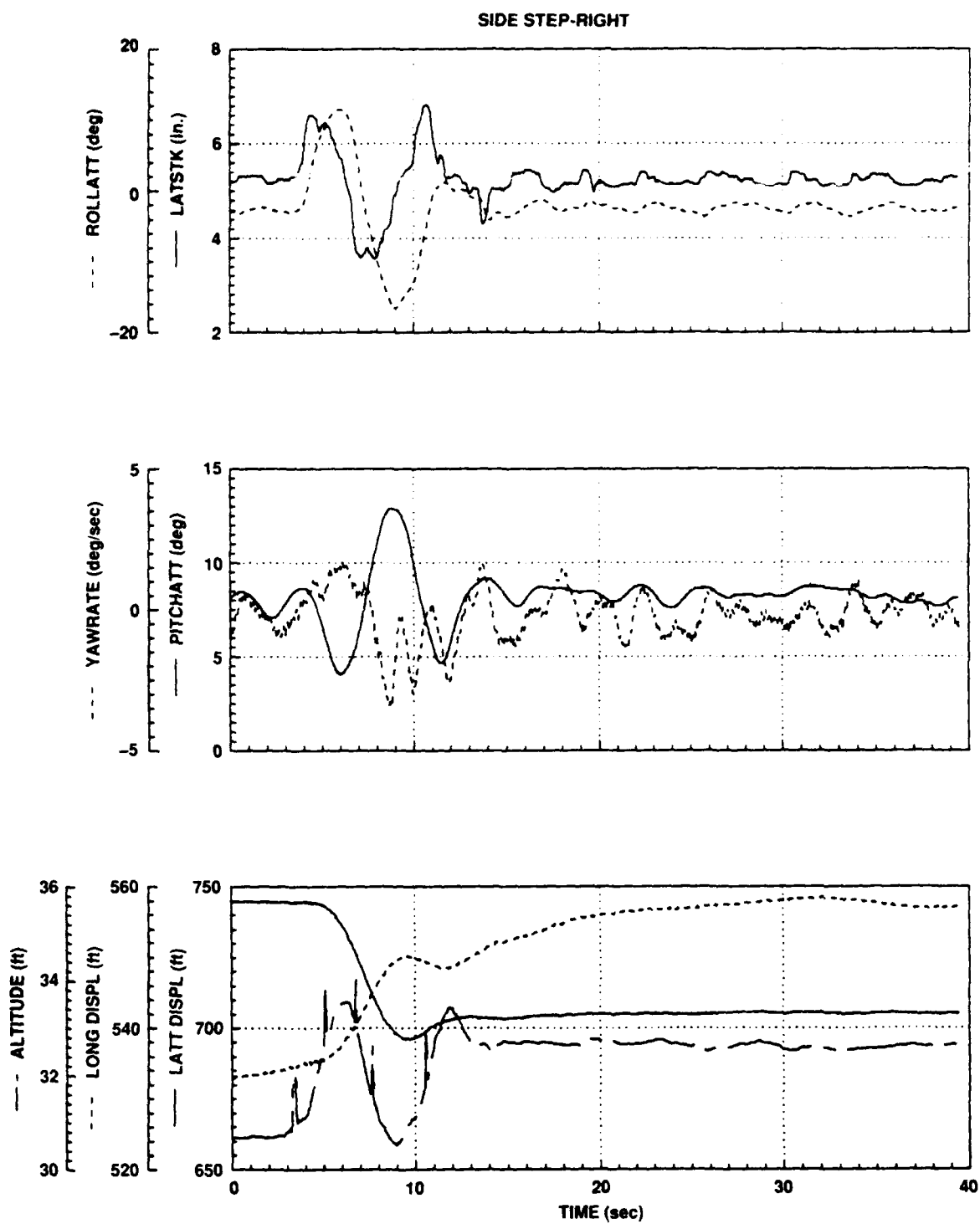
Figure C-10. Side-step time history data for flight (Pilot 3) (Continued).
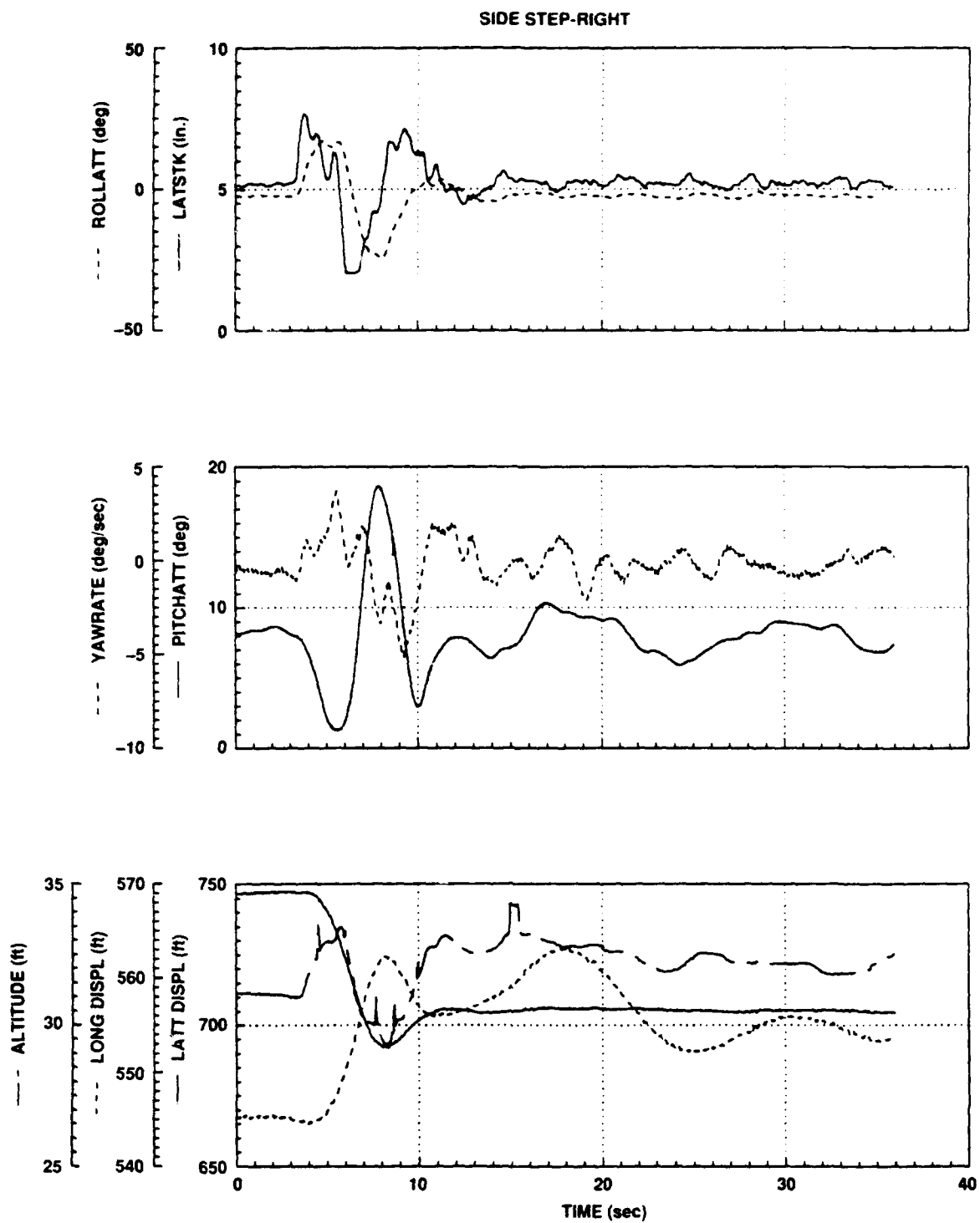
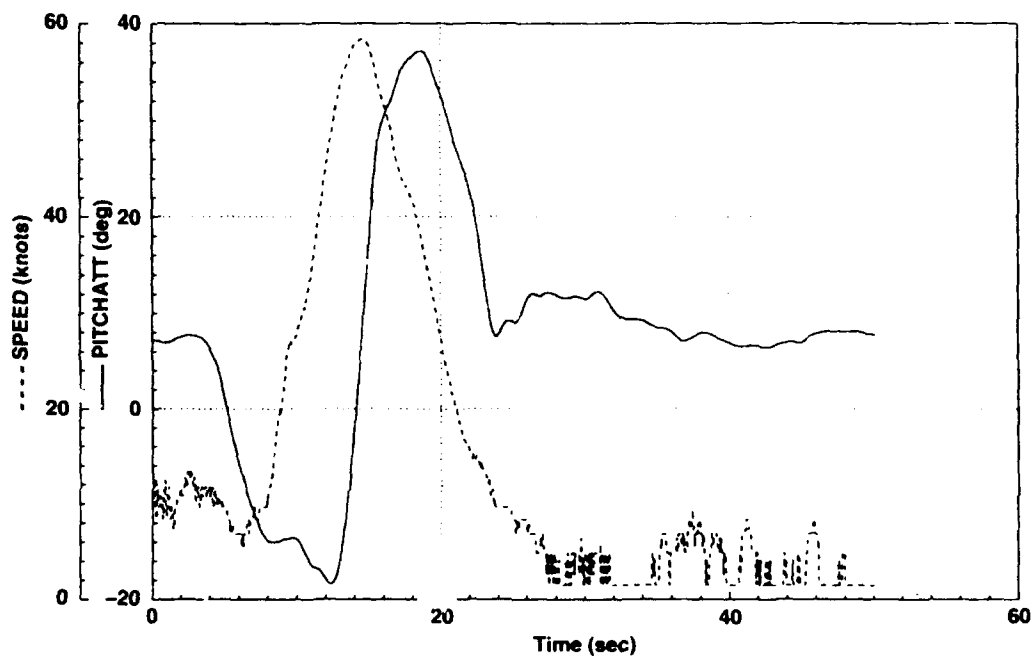Figure C-10. Side-step time history data for flight (Pilot 3) (Continued).

227
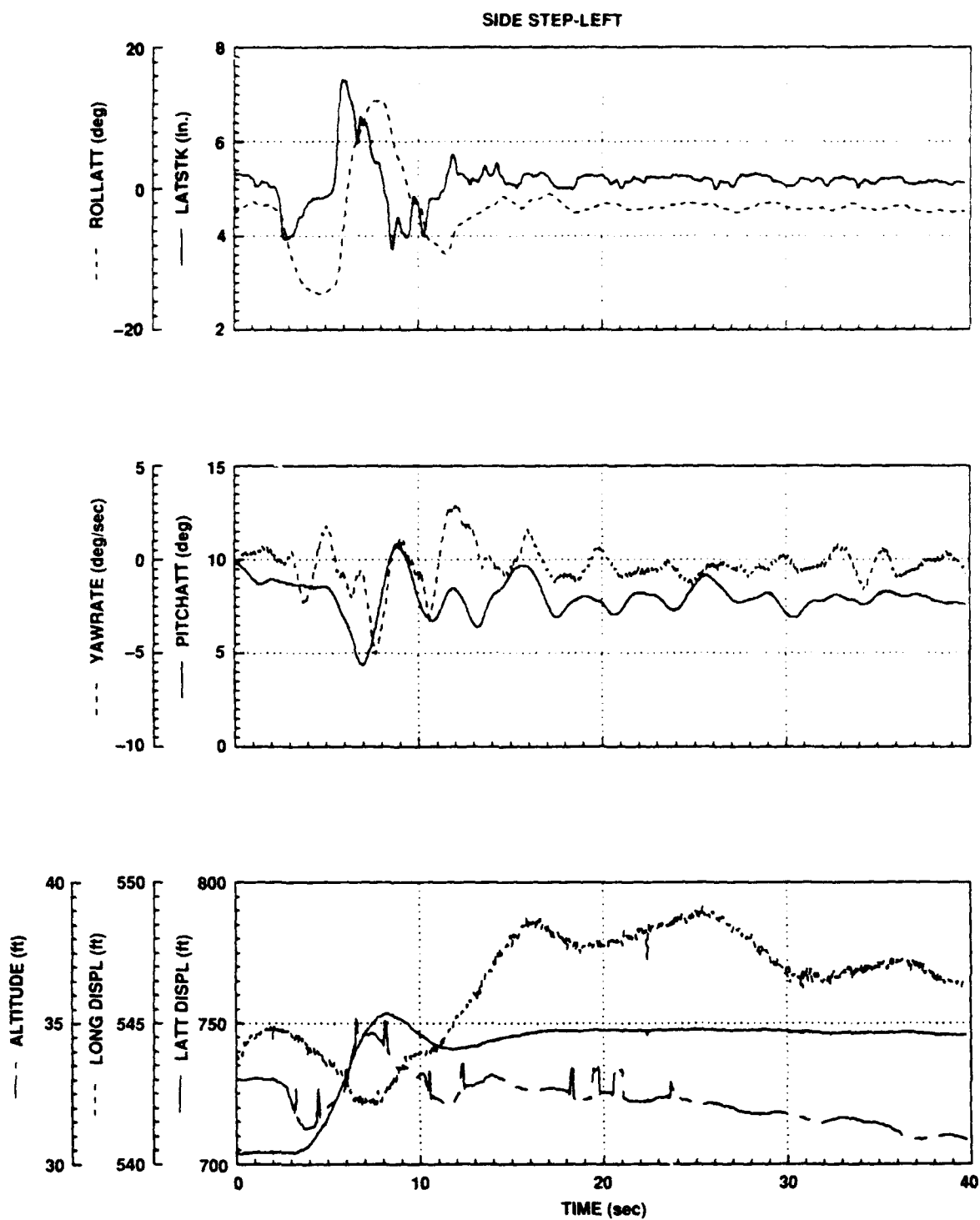
Figure C-10. Side-step time history data for flight (Pilot 3) (Continued).
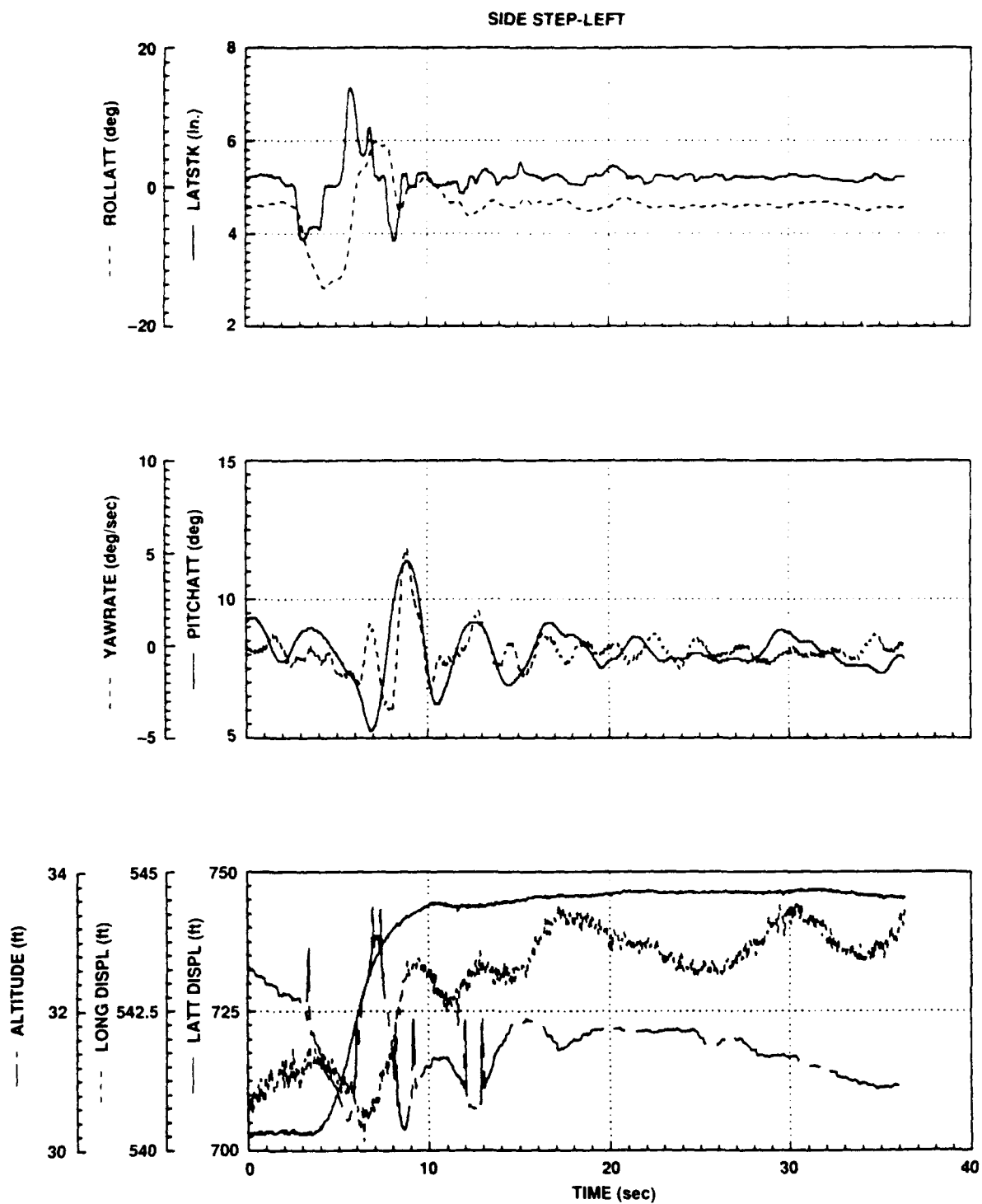
Figure C-10. Side-step time history data for flight (Pilot 3) (Continued).
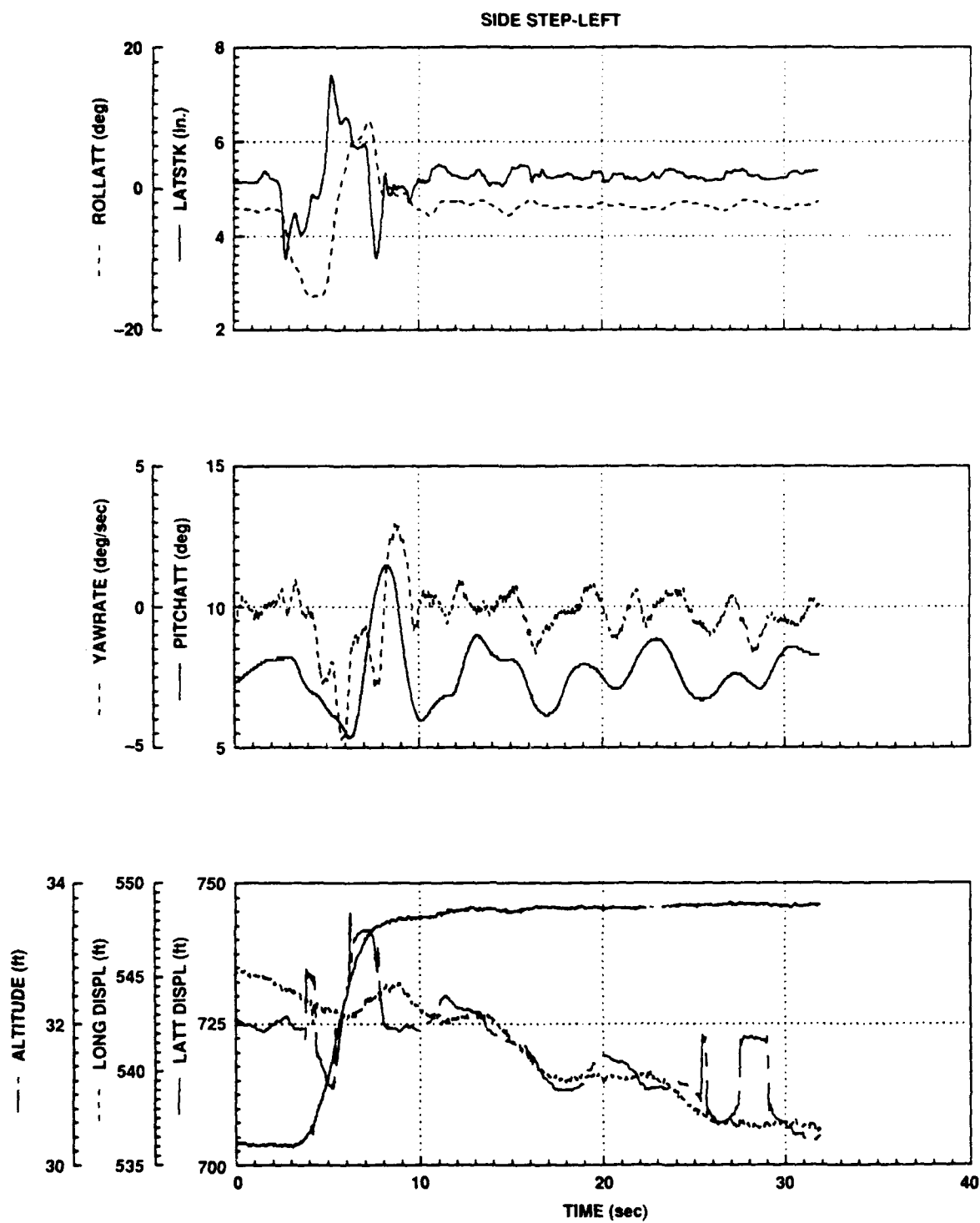
Figure C-10. Side-step time history data for flight (Pilot 3) (Concluded).
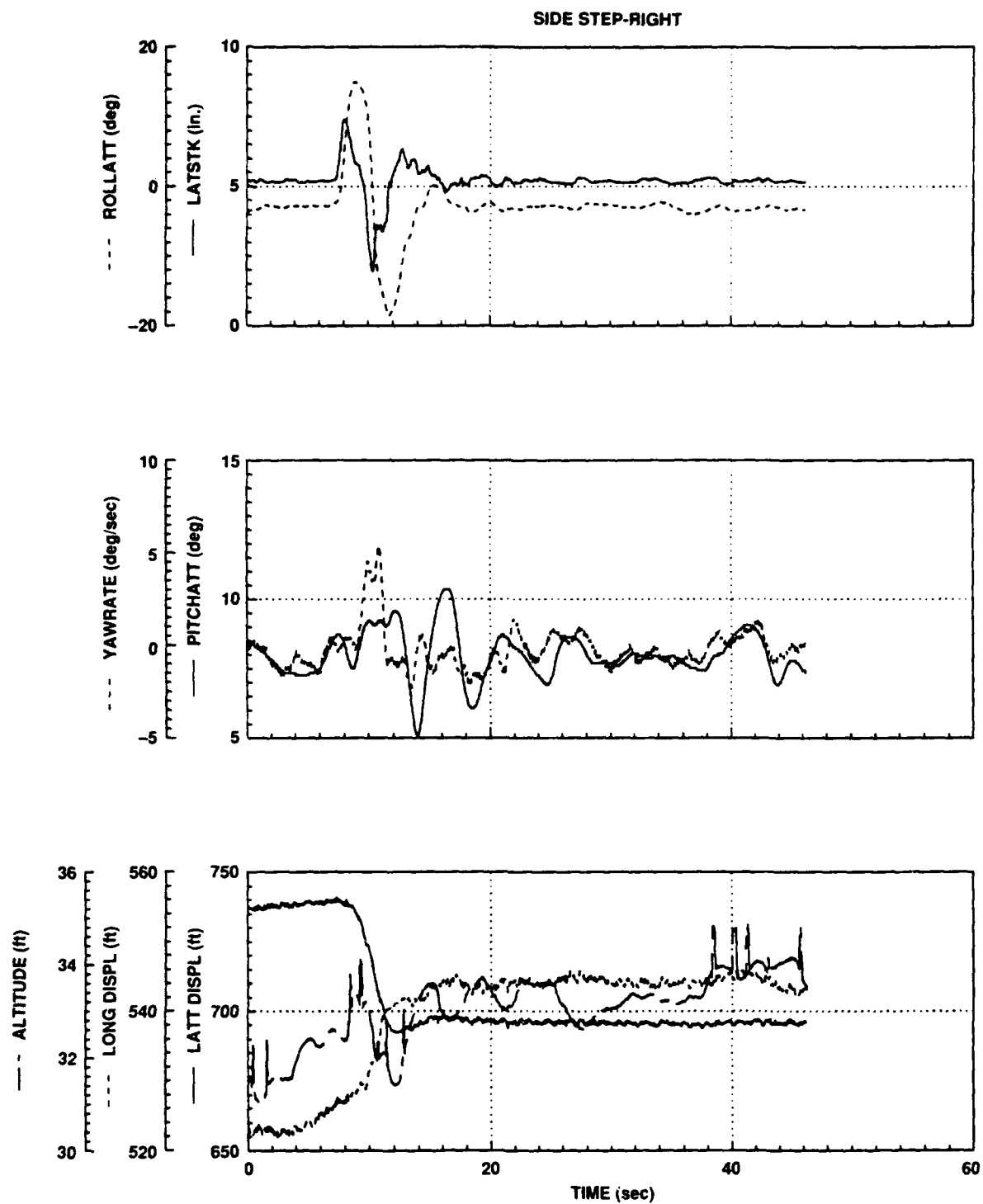
Figure C-11. Side-step time history data for flight (Pilot 4).
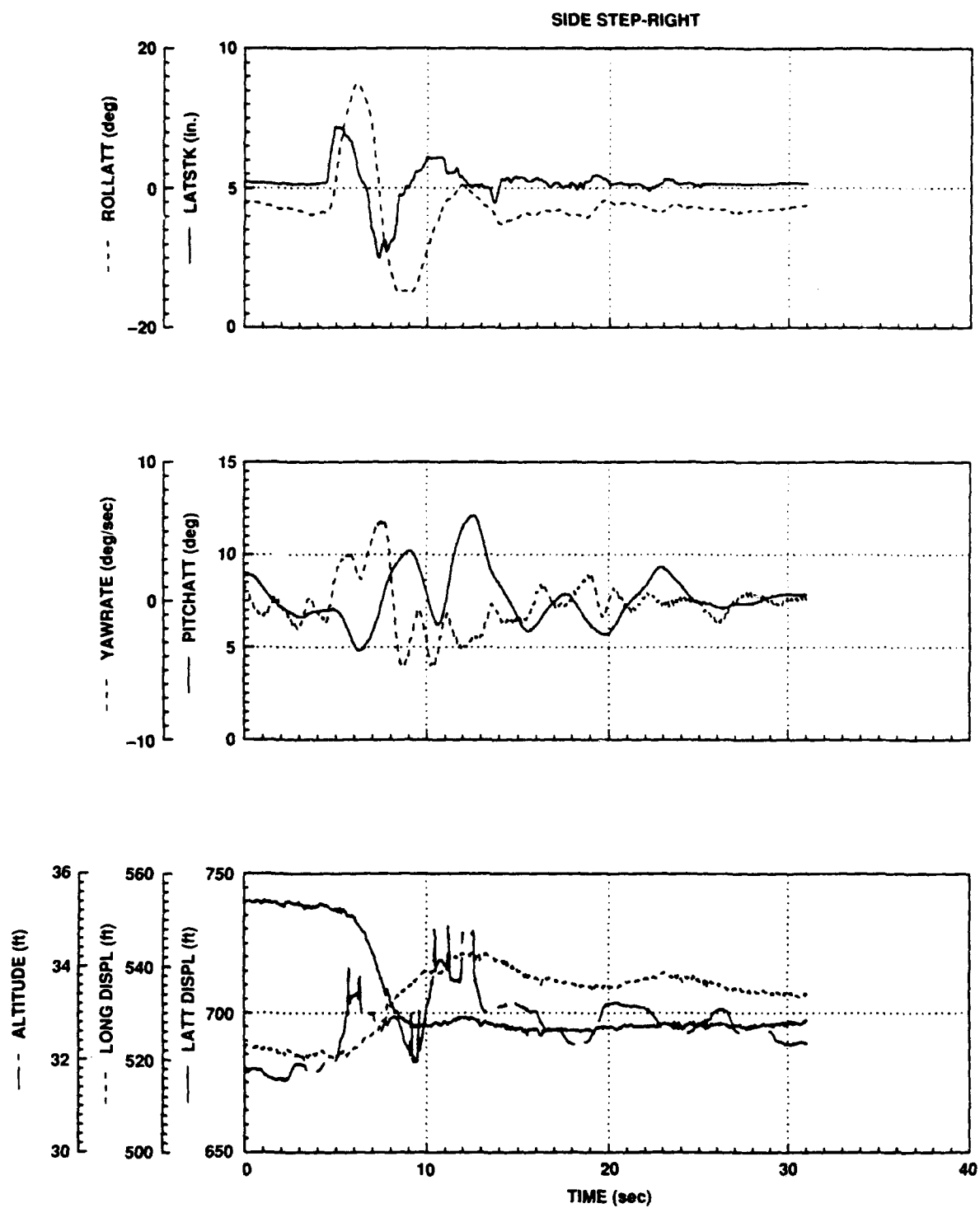
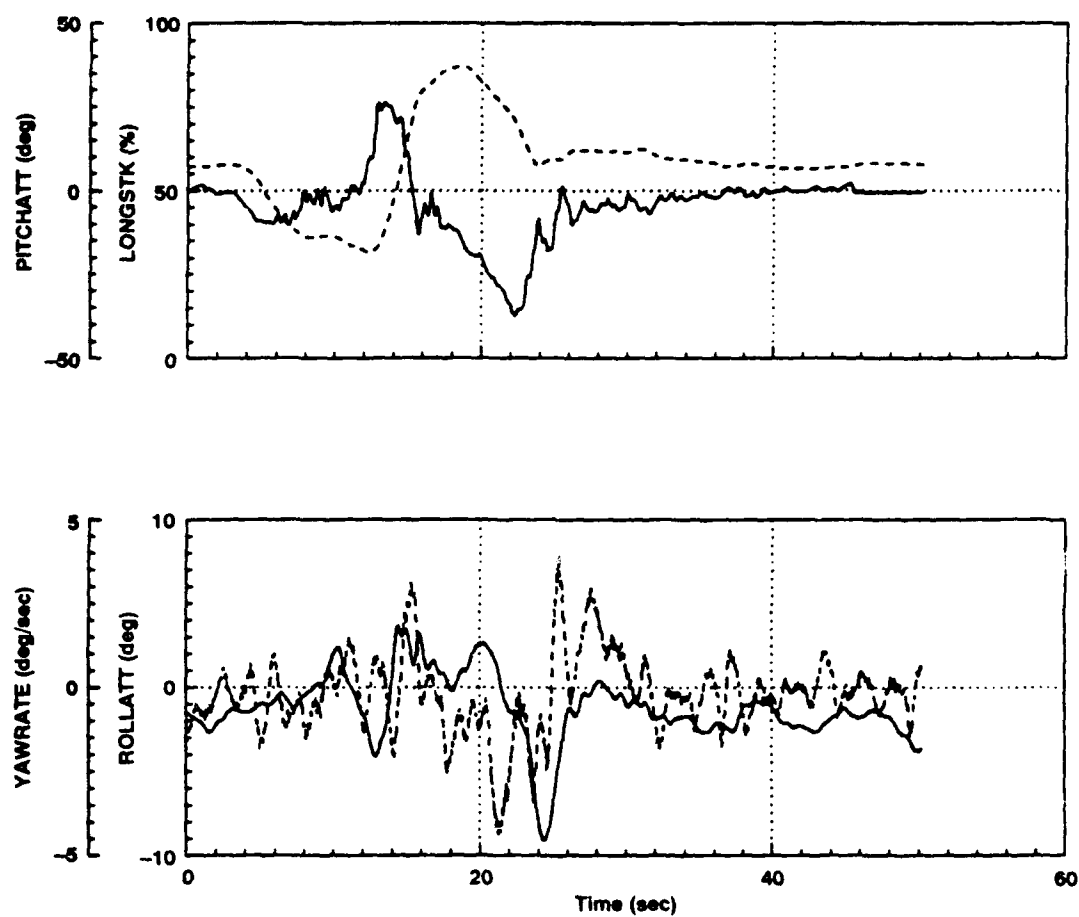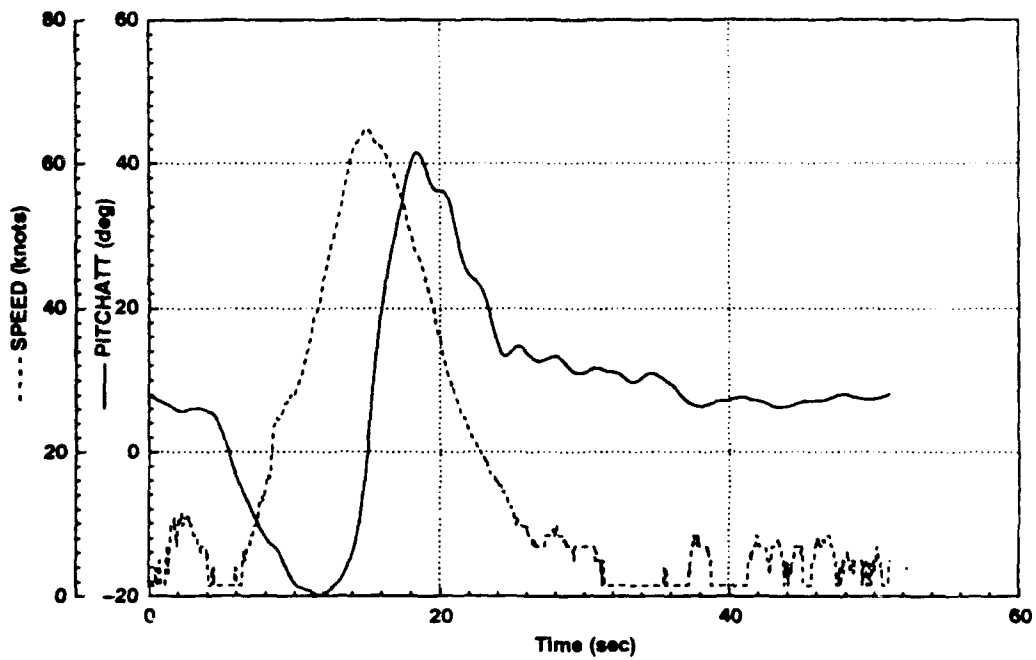Figure C-11. Side-step time history data for flight (Pilot 4) (Continued).
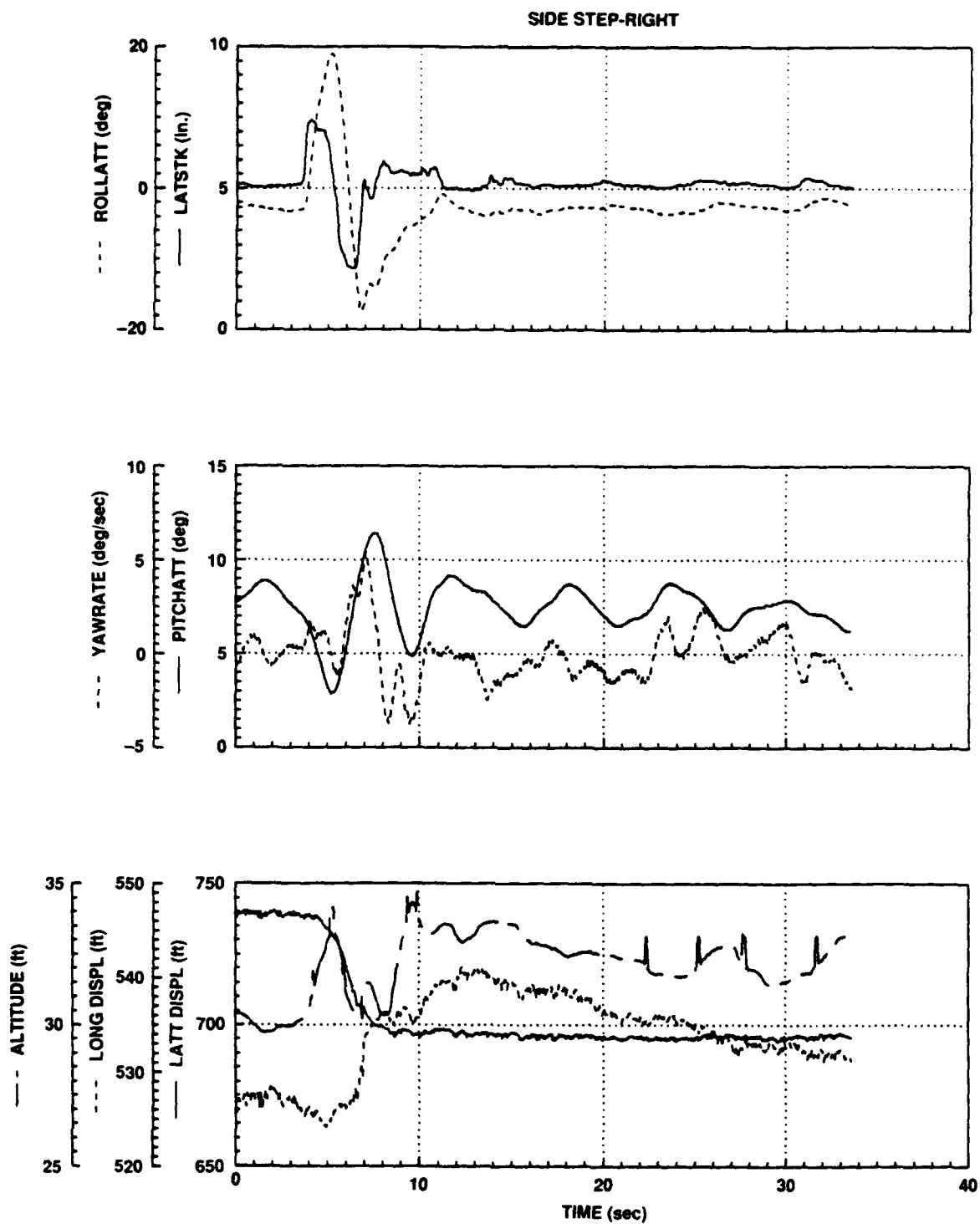
Figure C-11. Side-step time history data for flight (Pilot 4) (Continued).

233

Figure C-11. Side-step time history data for flight (Pilot 4) (Continued).

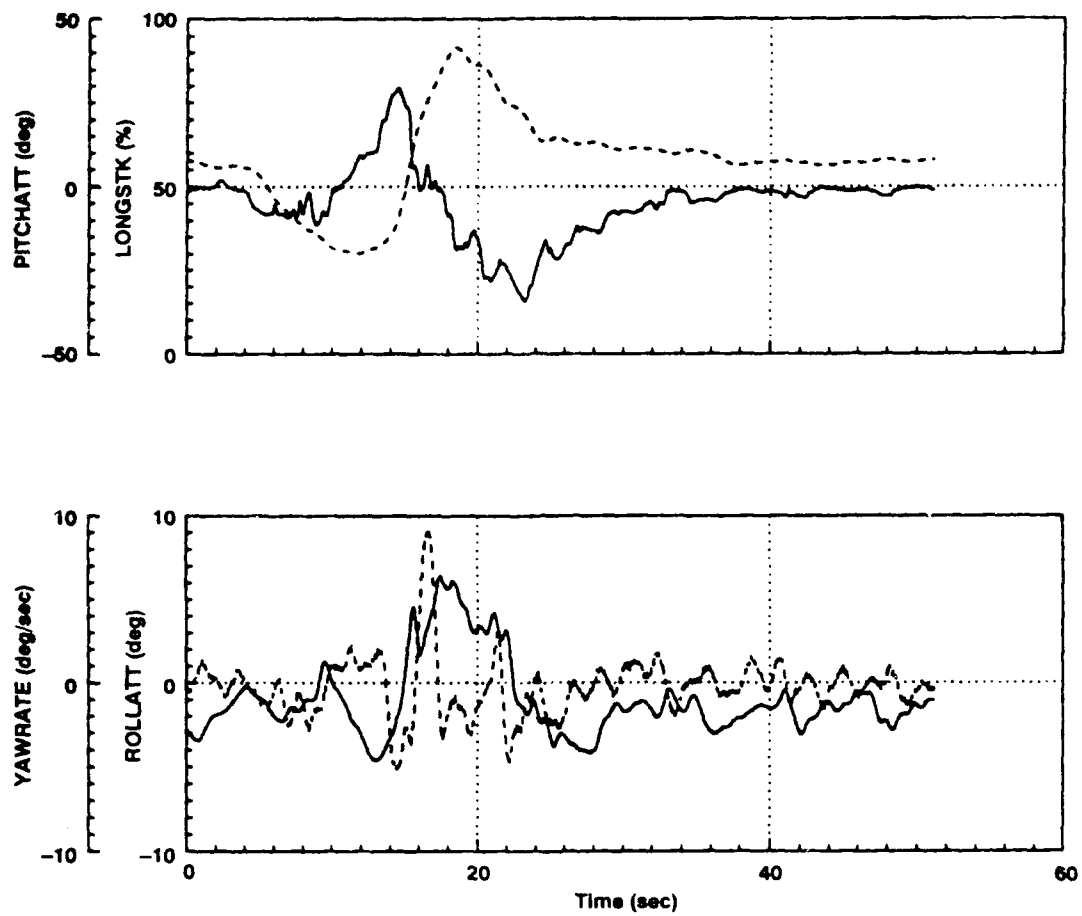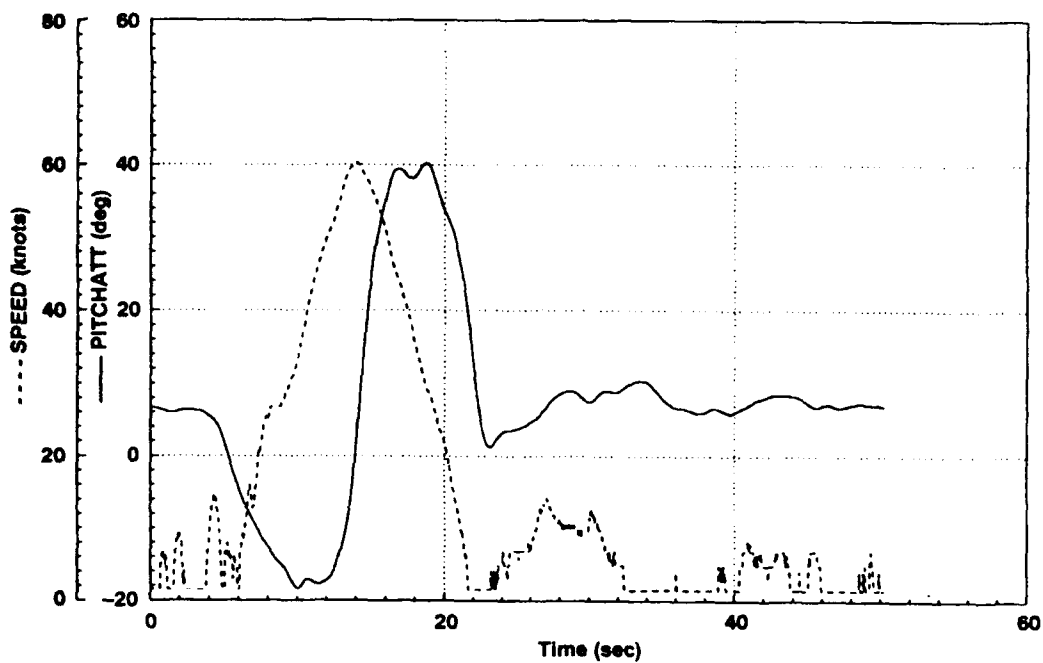Figure C-11. Side-step time history data for flight (Pilot 4) (Continued).

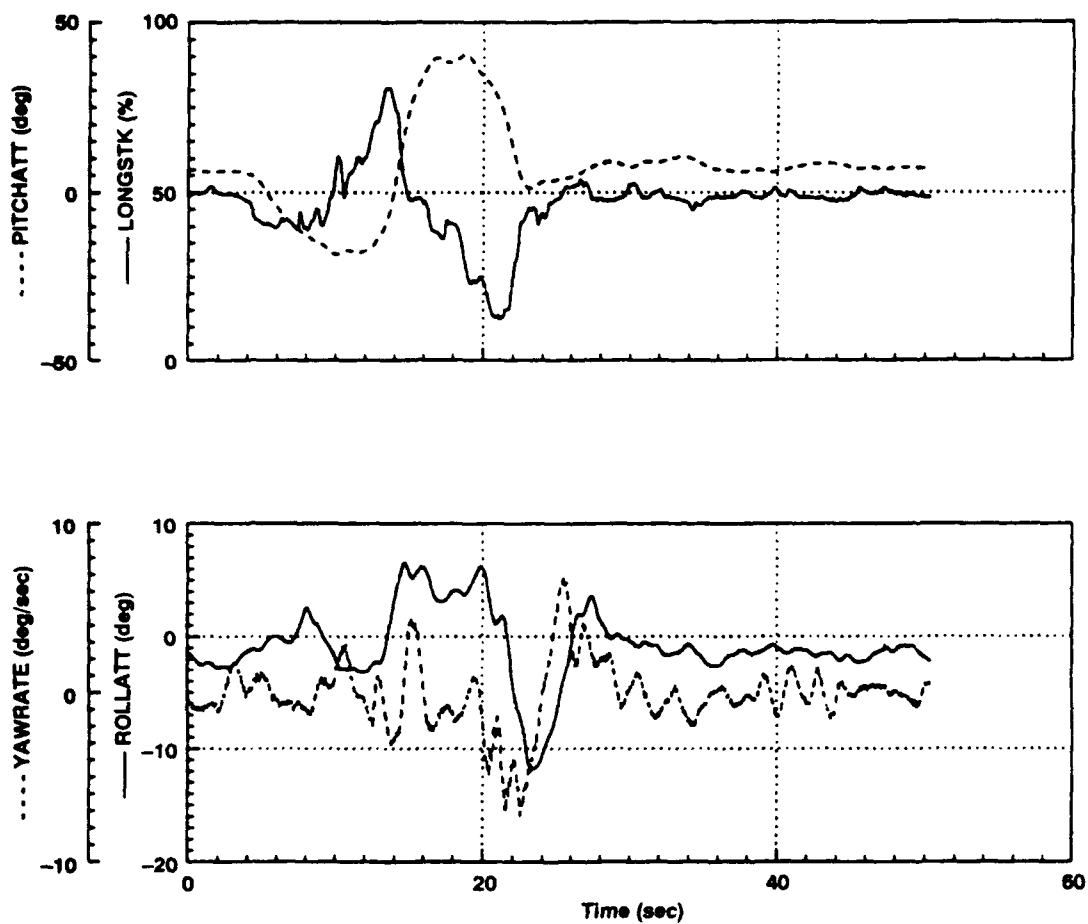Figure C-11. Side-step time history data for flight (Pilot 4) (Concluded).
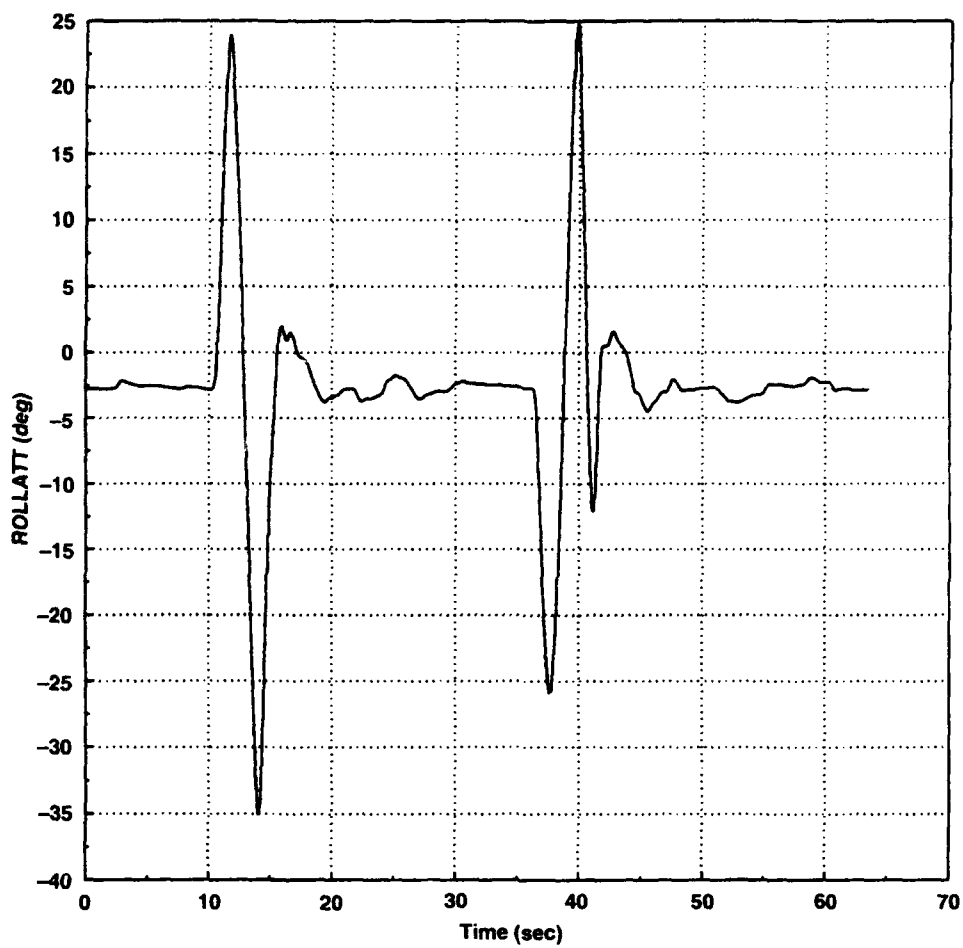
Figure C-12. Side-step time history data for simulator (Pilot 2).

Figure C-12. Side-step time history data for simulator (Pilot 2) (Continued).
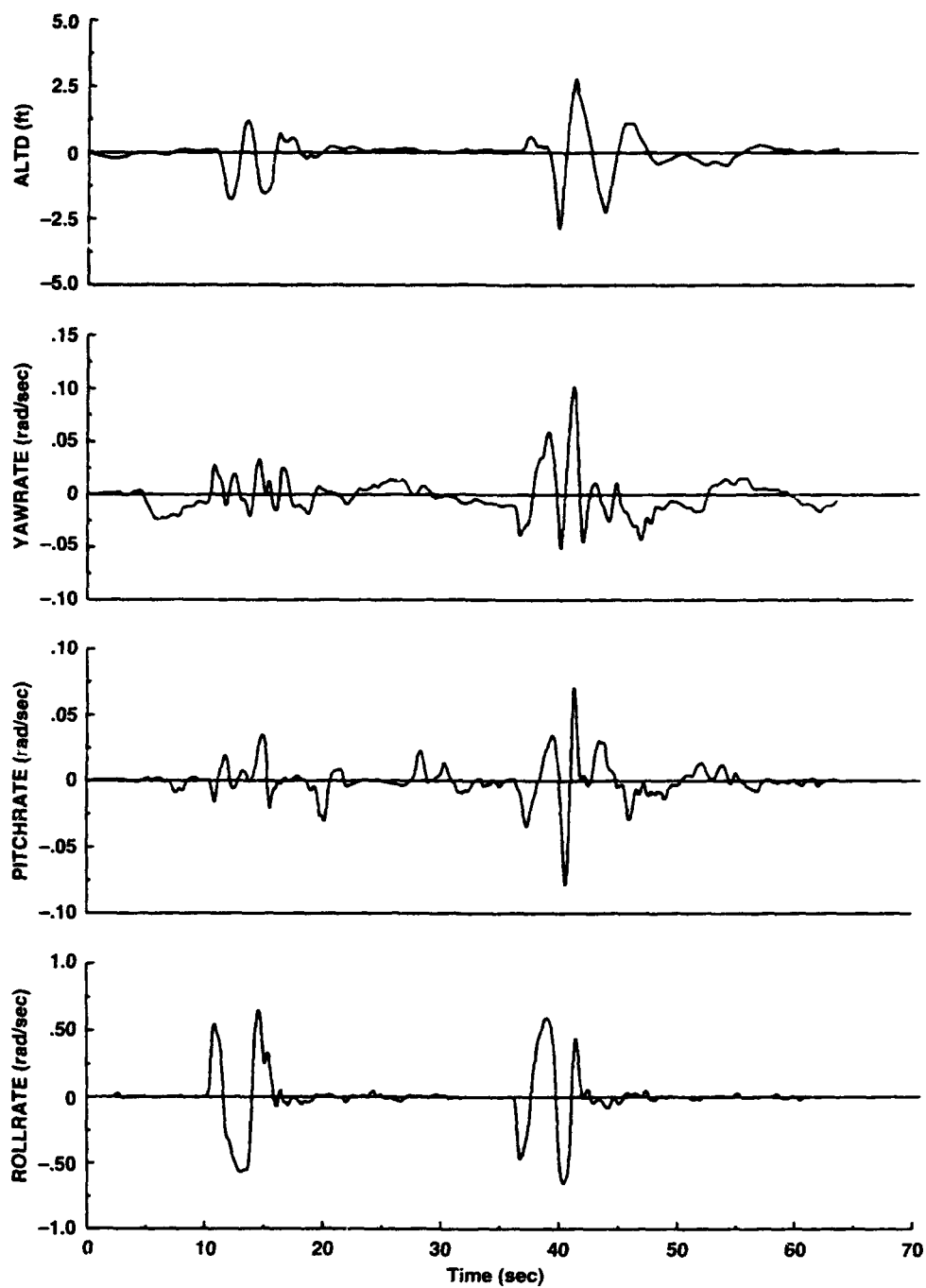
Figure C-12. Side-step time history data for simulator (Pilot 2) (Continued).

Figure C-12. Side-step time history data for simulator (Pilot 2) (Continued).
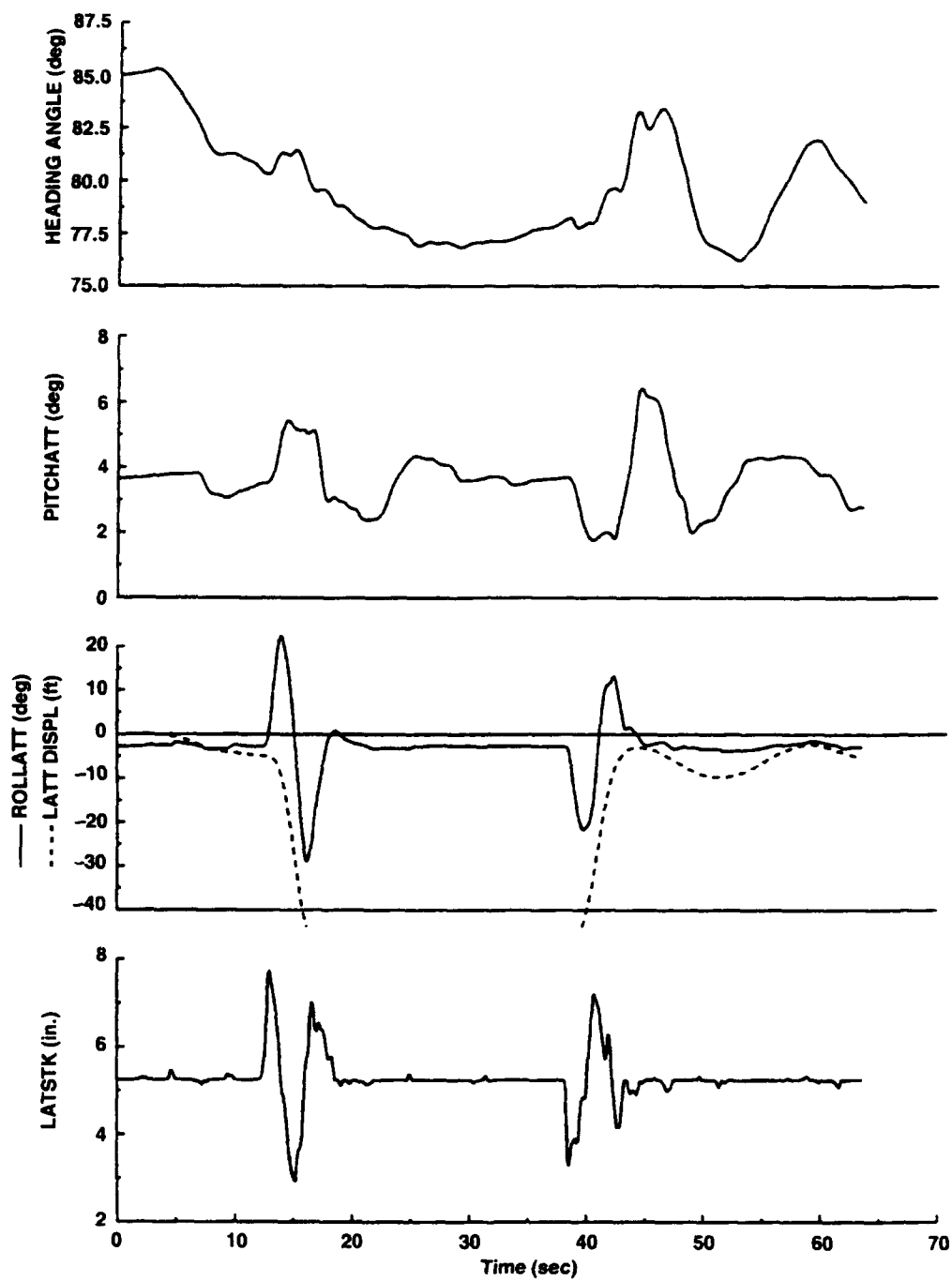
Figure C-12. Side-step time history data for simulator (Pilot 2) (Continued).
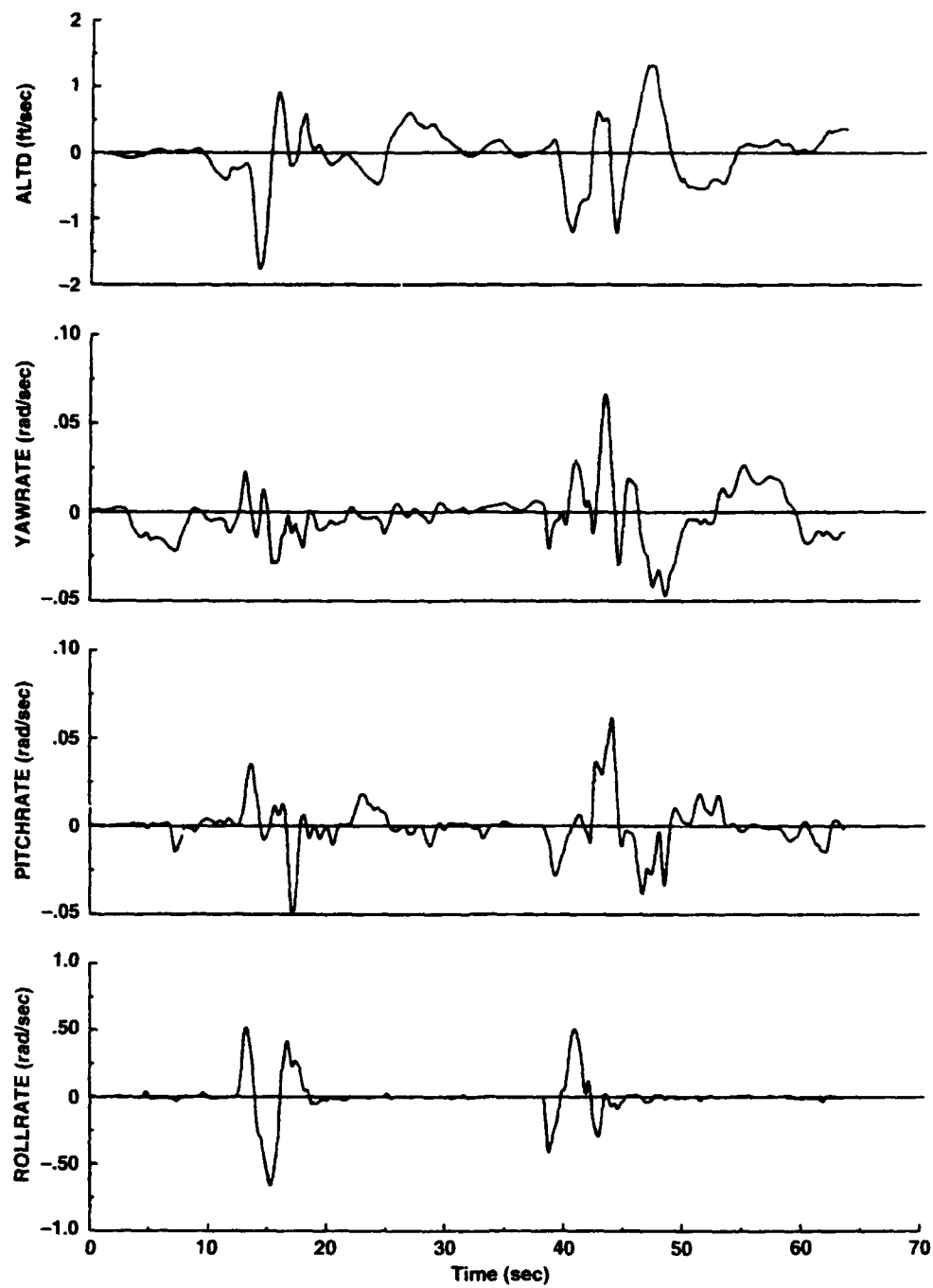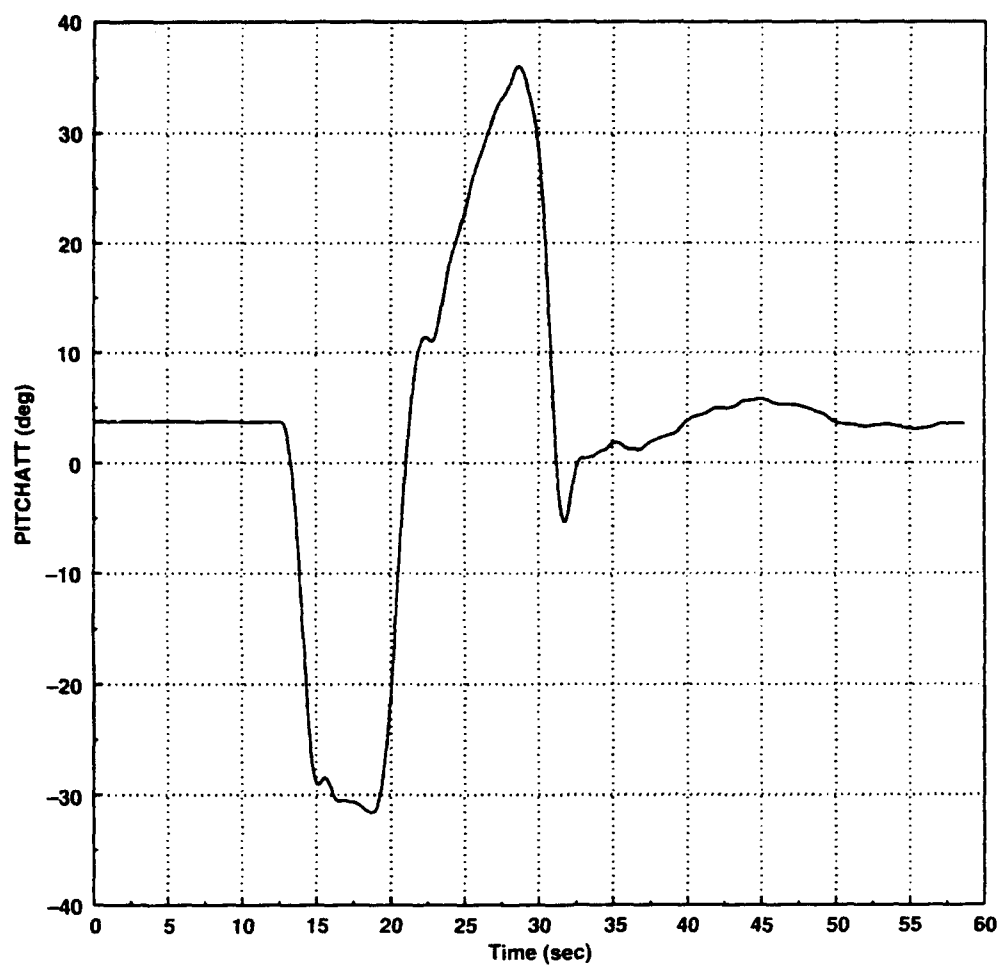
Figure C-12. Side-step time history data for simulator (Pilot 2) (Continued).
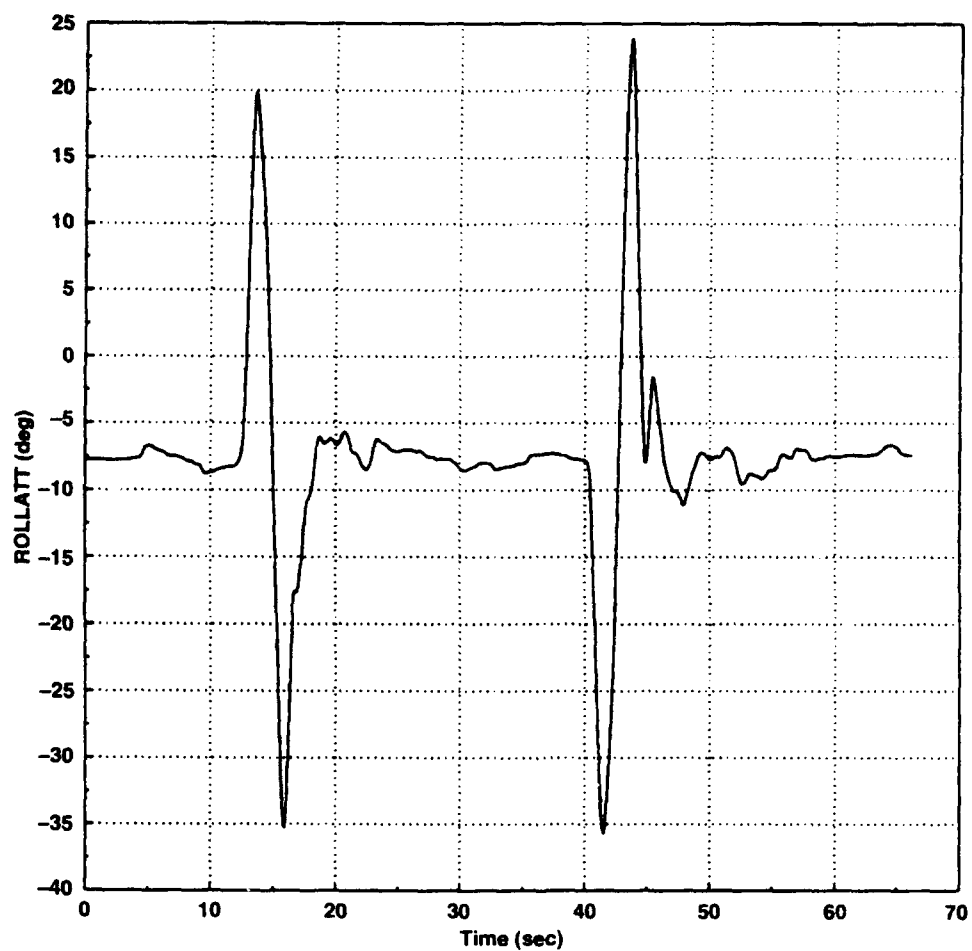
Figure C-12. Side-step time history data for simulator (Pilot 2) (Continued).

Figure C-12. Side-step time history data for simulator (Pilot 2) (Continued).
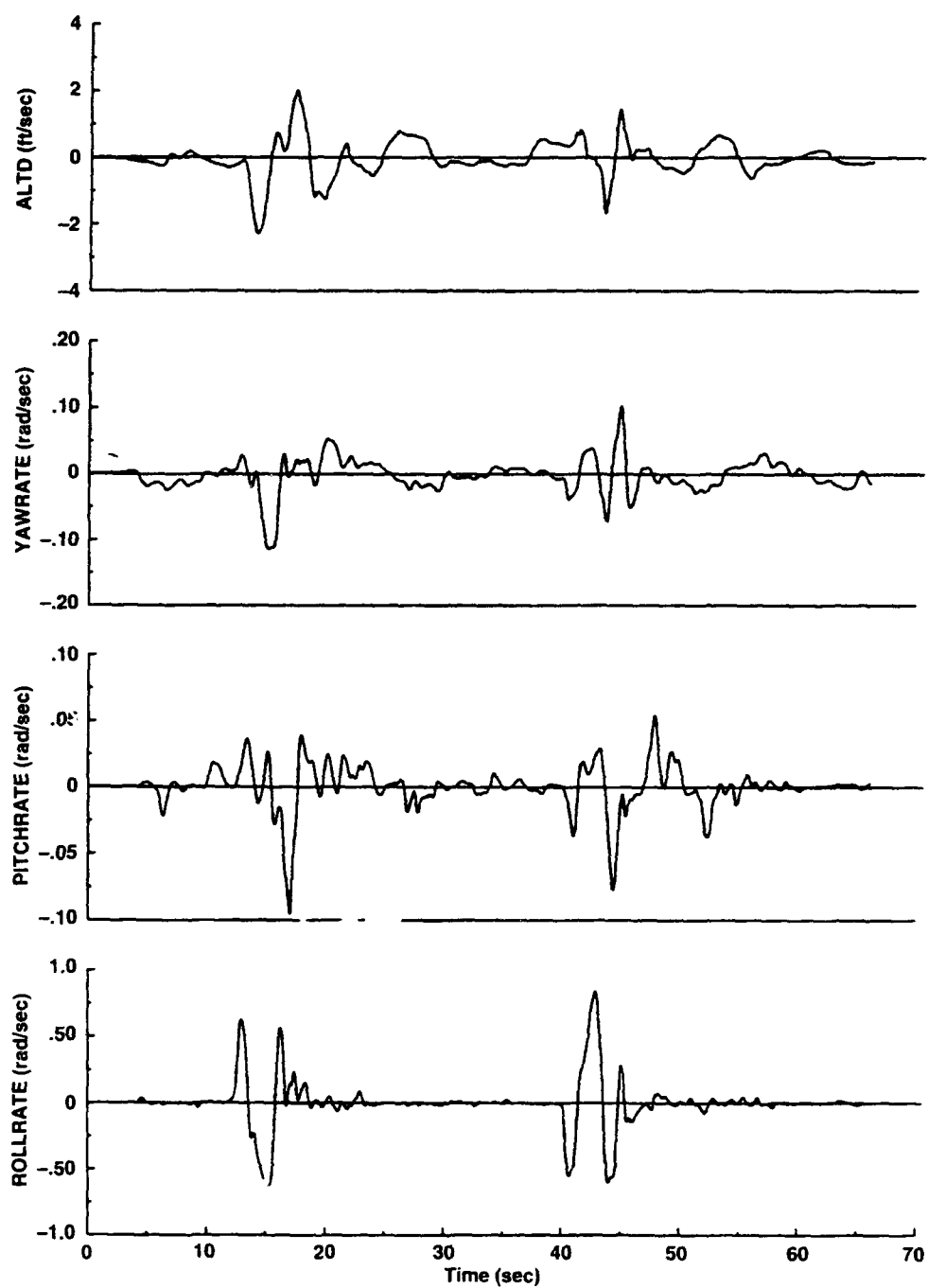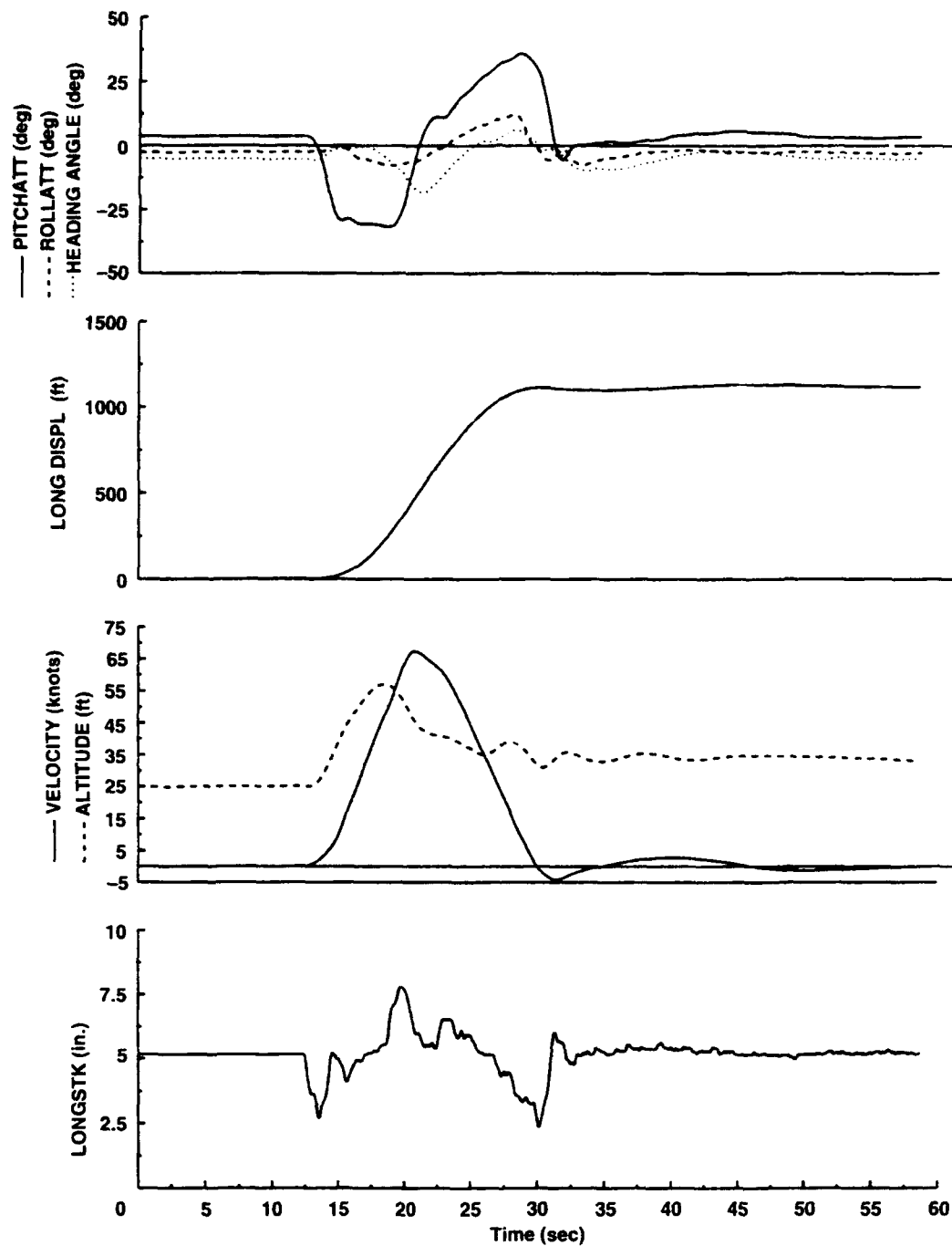
Figure C-12. Side-step time history data for simulator (Pilot 2) (Concluded).
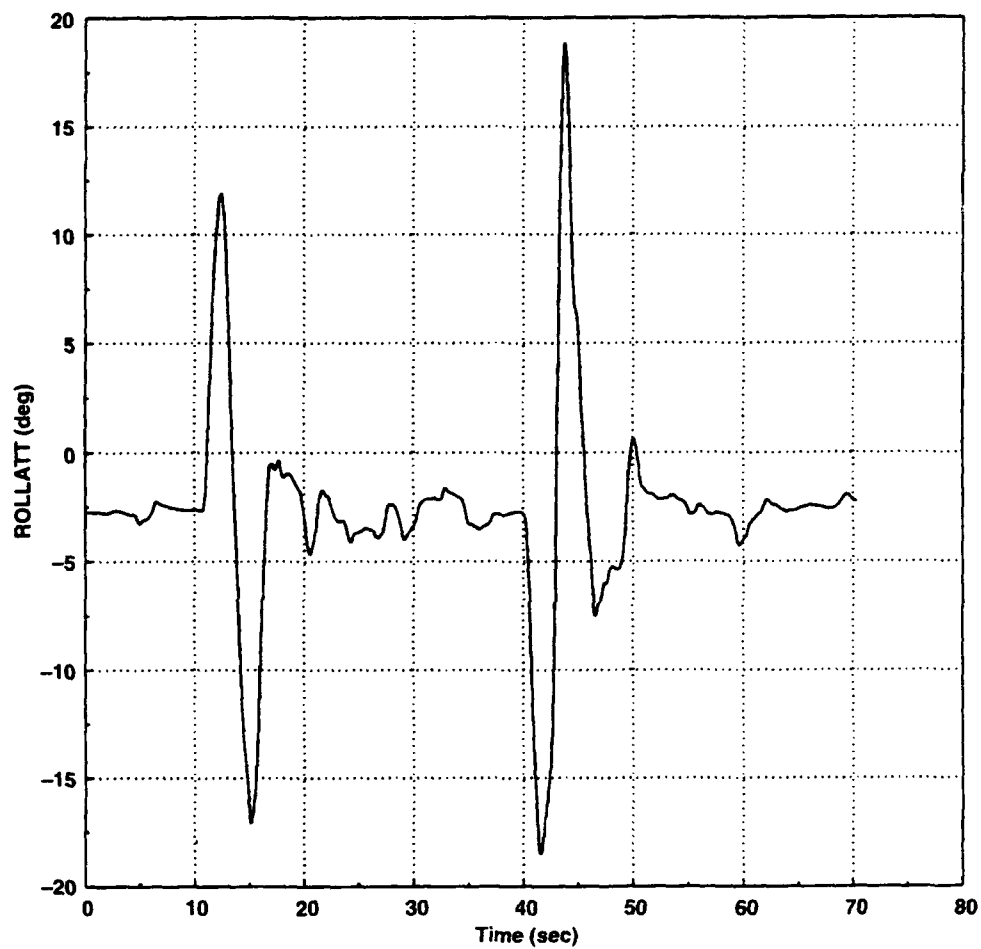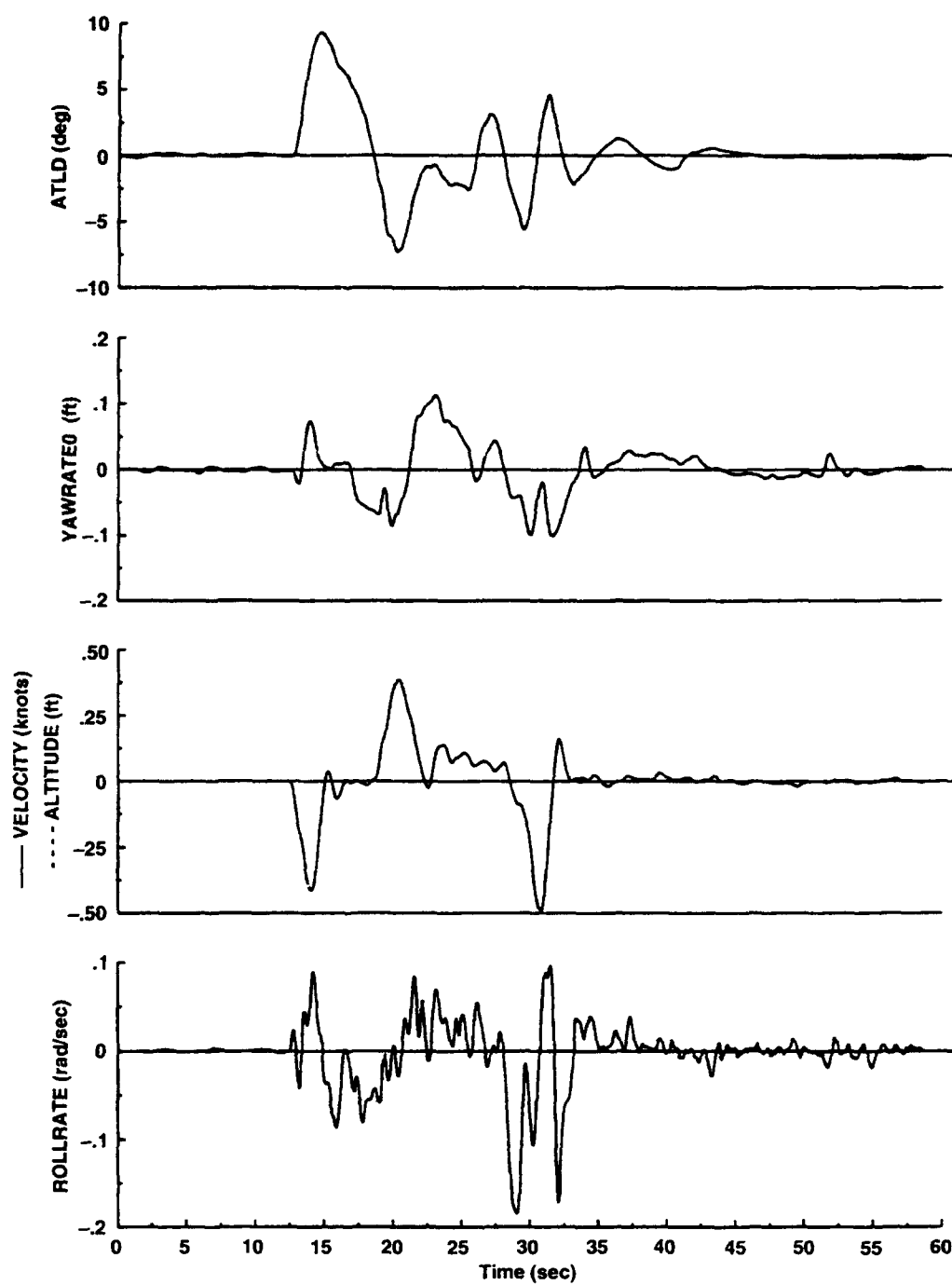
Figure C-13. Side-step time history data for simulator (Pilot 4).

Figure C-13. Side-step time history data for simulator (Pilot 4) (Continued).
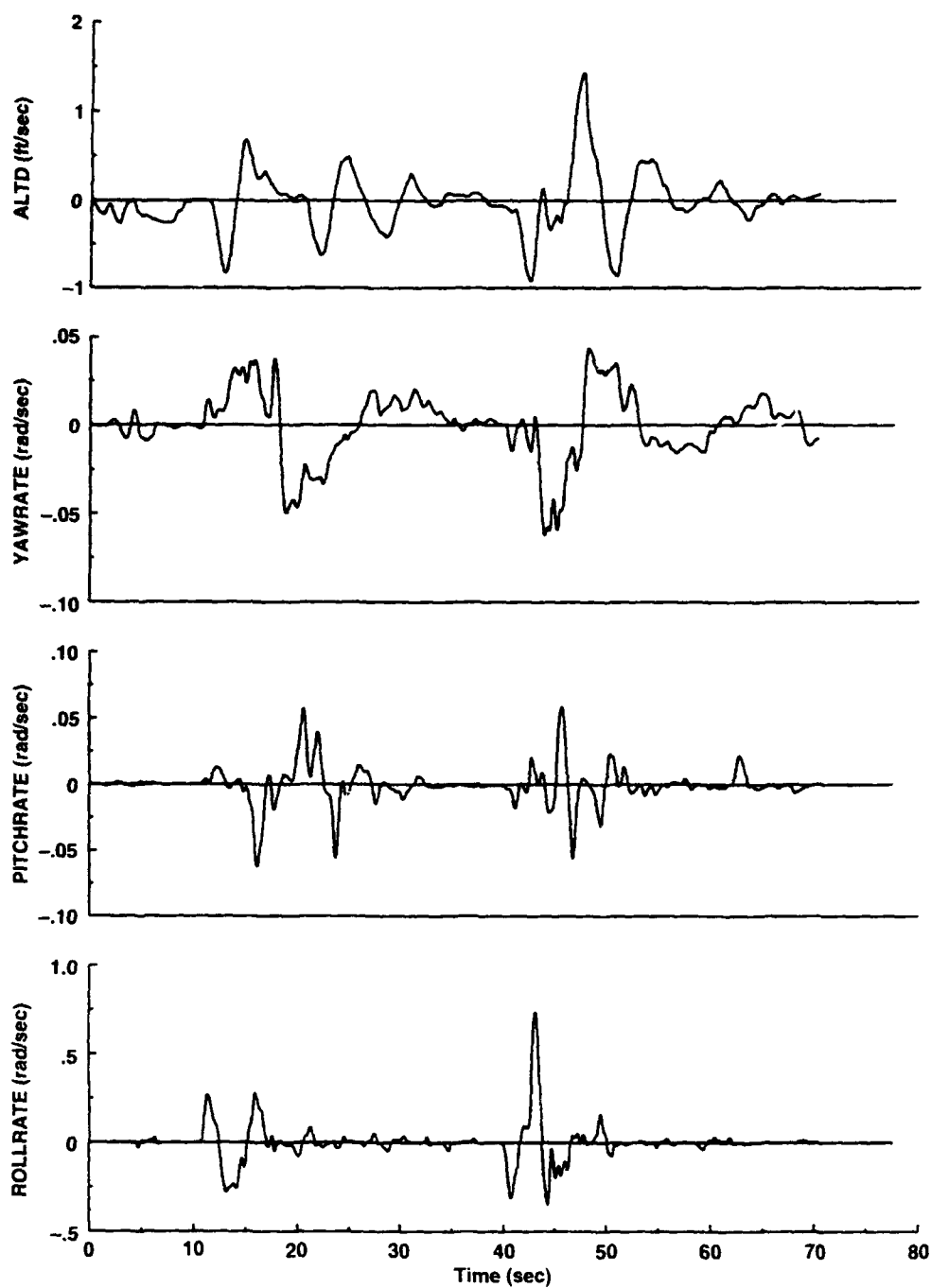
Figure C-13. Side-step time history data for simulator (Pilot 4) (Continued).

Figure C-13. Side-step time history data for simulator (Pilot 4) (Continued).

Figure C-13. Side-step time history data for simulator (Pilot 4) (Continued).

Figure C-13. Side-step time history data for simulator (Pilot 4) (Continued).

Figure C-13. Side-step time history data for simulator (Pilot 4) (Continued).

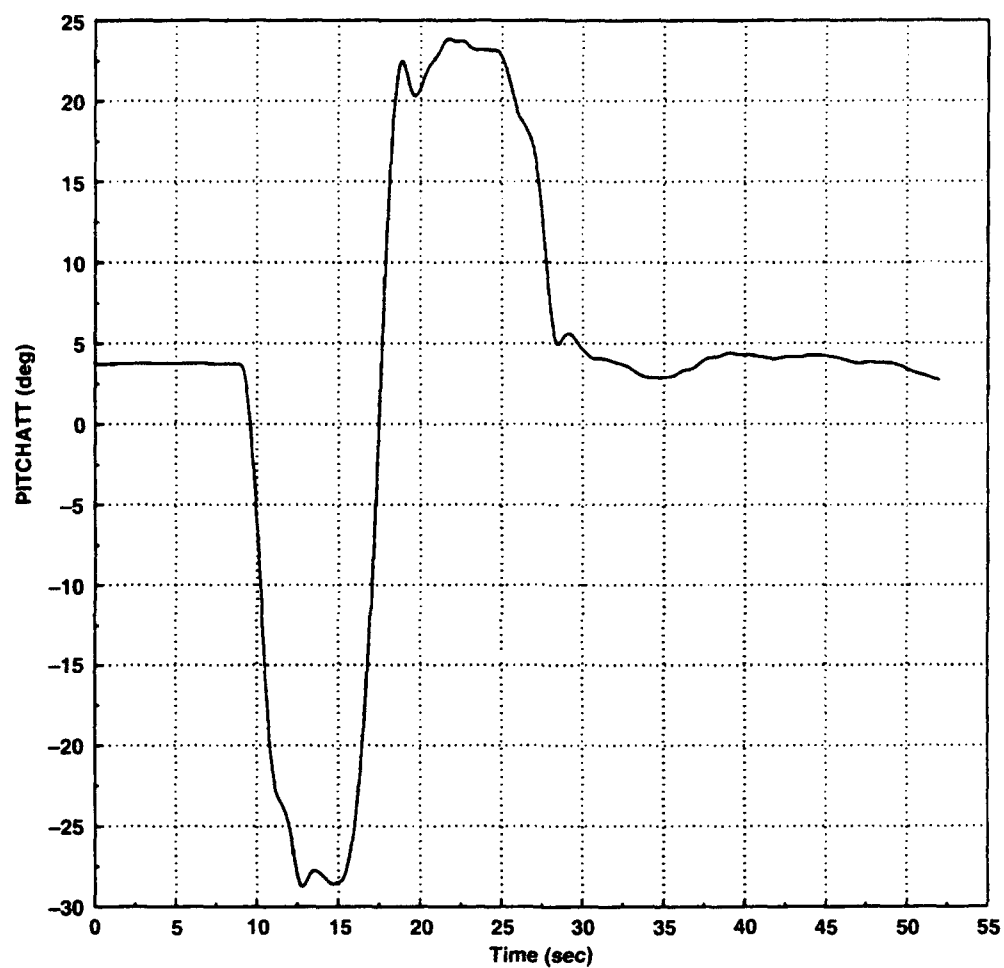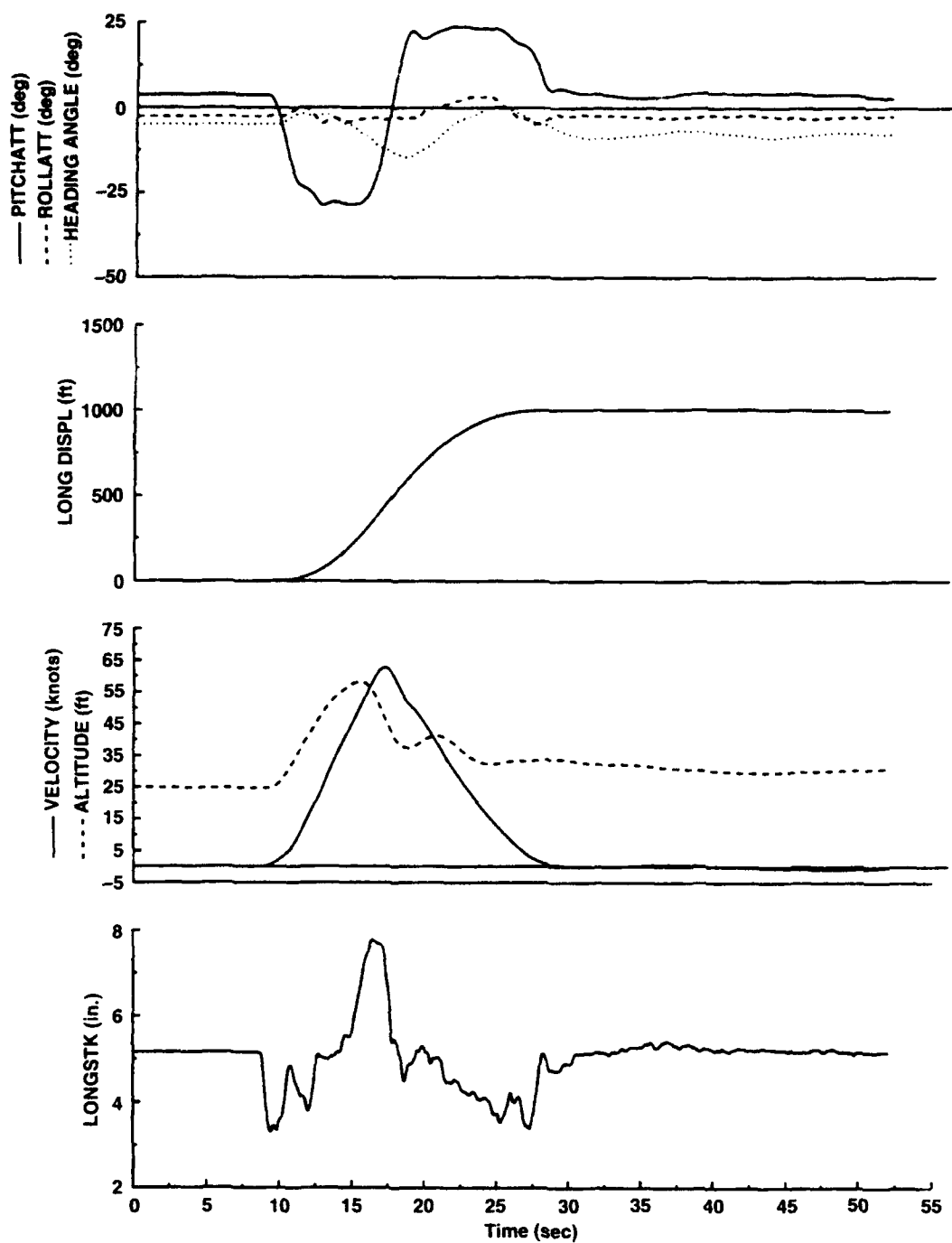Figure C-13. Side-step time history data for simulator (Pilot 4) (Continued).

Figure C-13. Side-step time history data for simulator (Pilot 4) (Concluded).

254
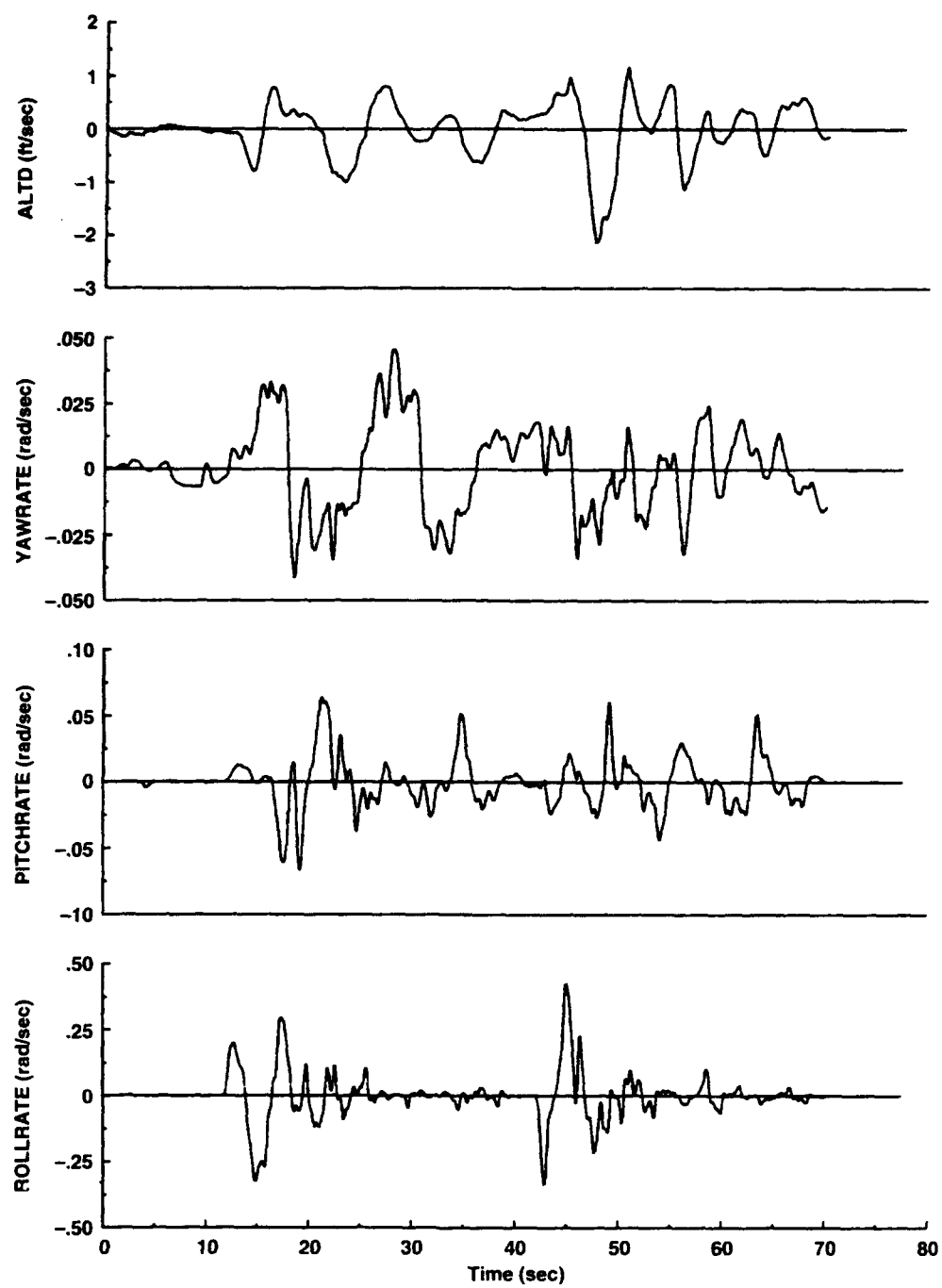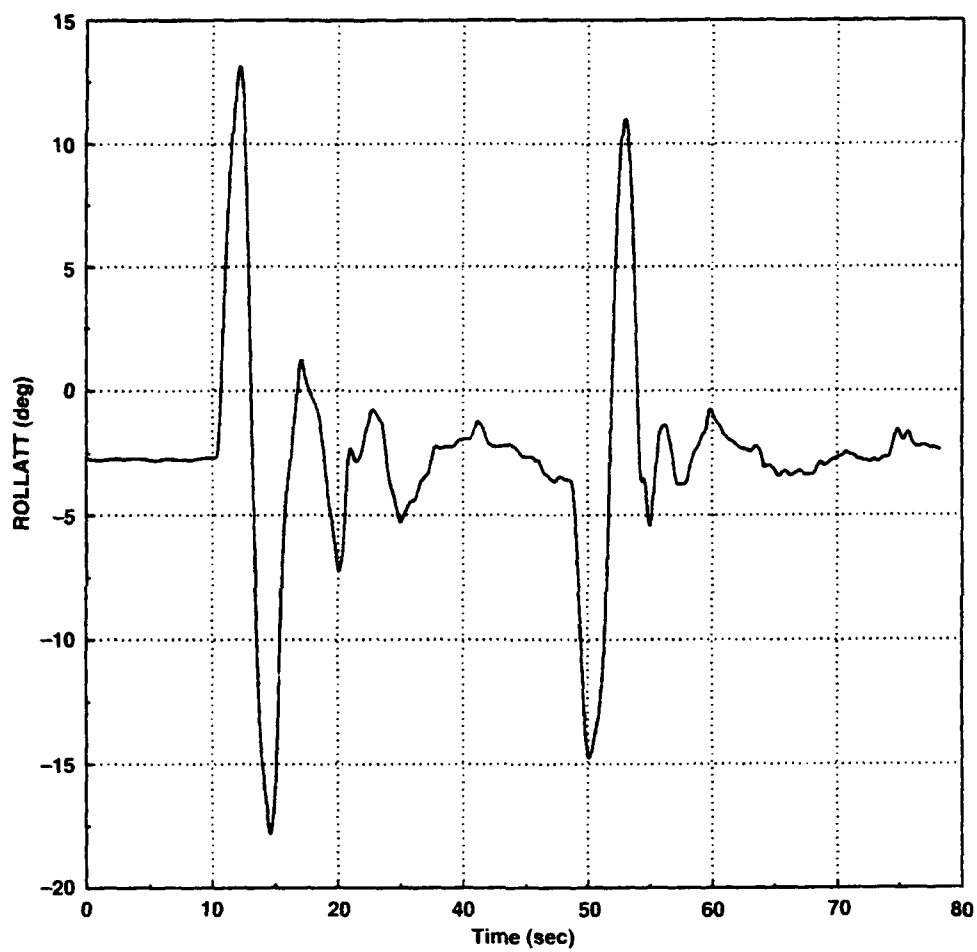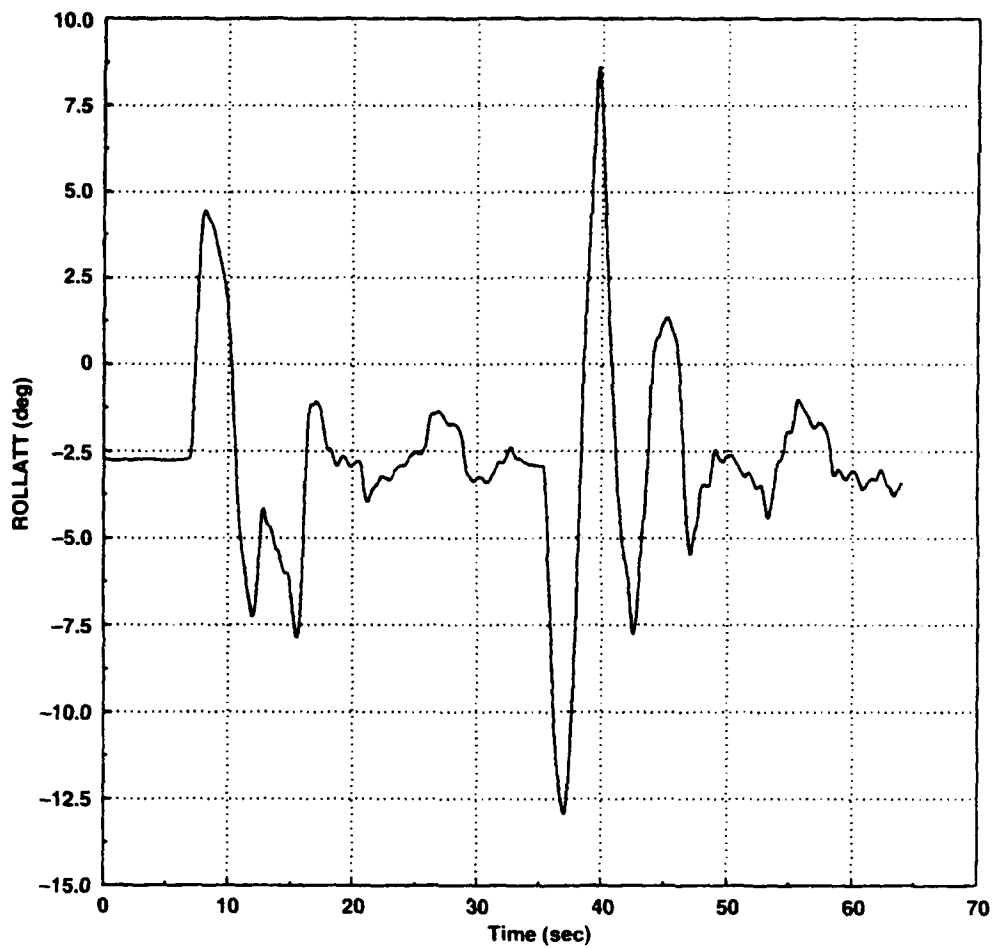
Figure C-14. Side-step time history data for simulator (Pilot 5).

Figure C-14. Side-step time history data for simulator (Pilot 5) (Continued).
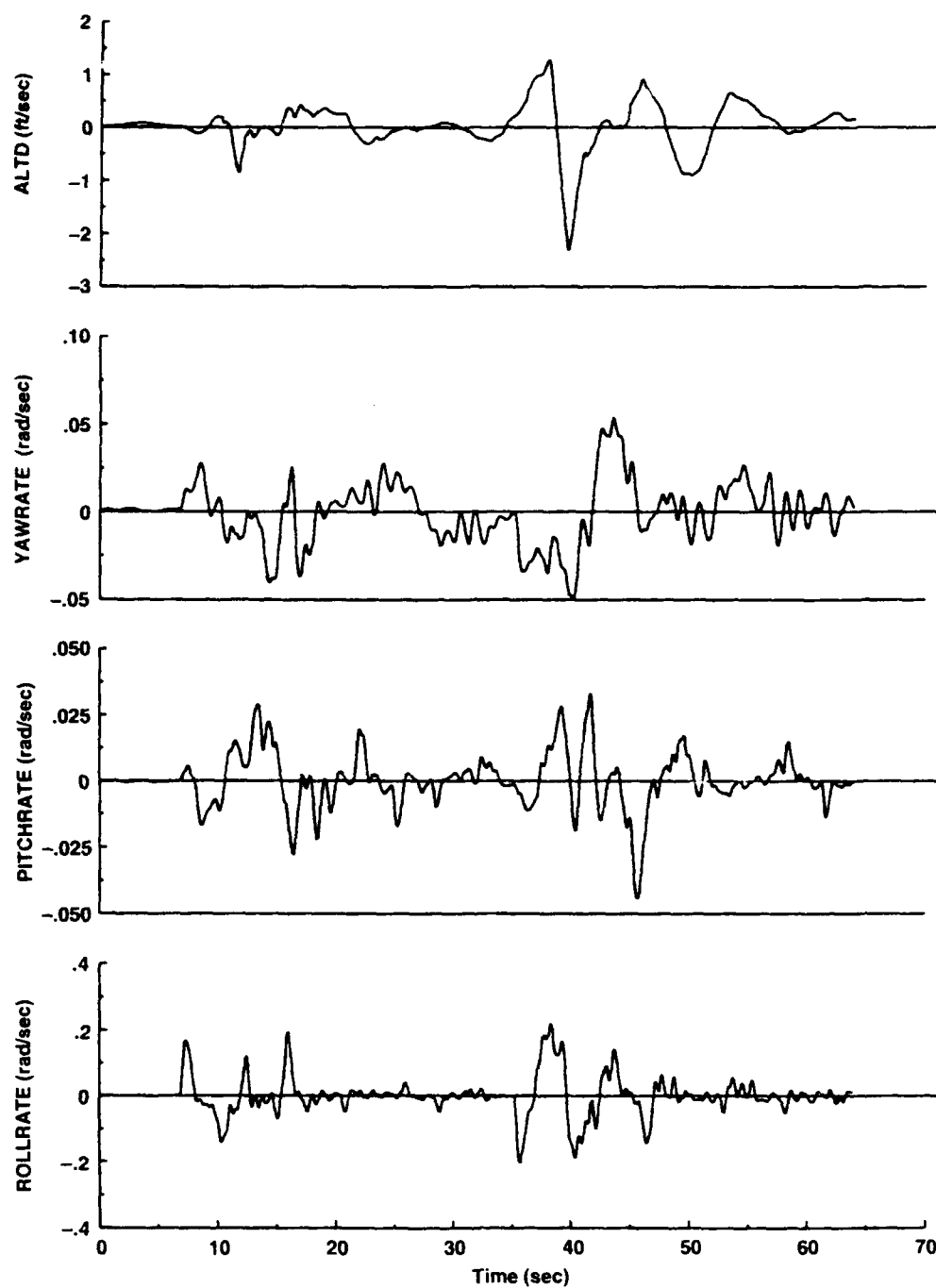
Figure C-14. Side-step time history data for simulator (Pilot 5) (Continued).

Figure C-14. Side-step time history data for simulator (Pilot 5) (Continued).
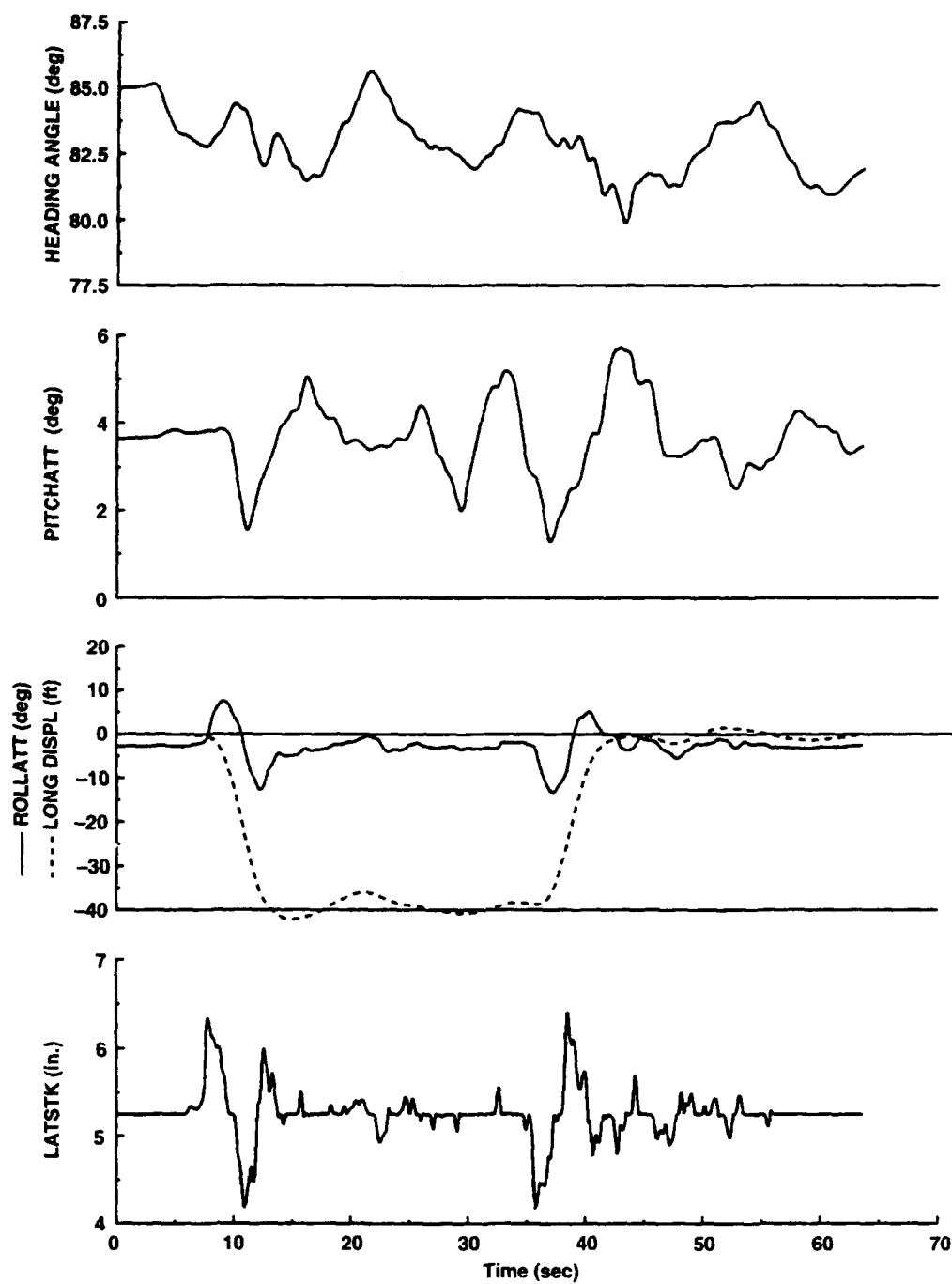
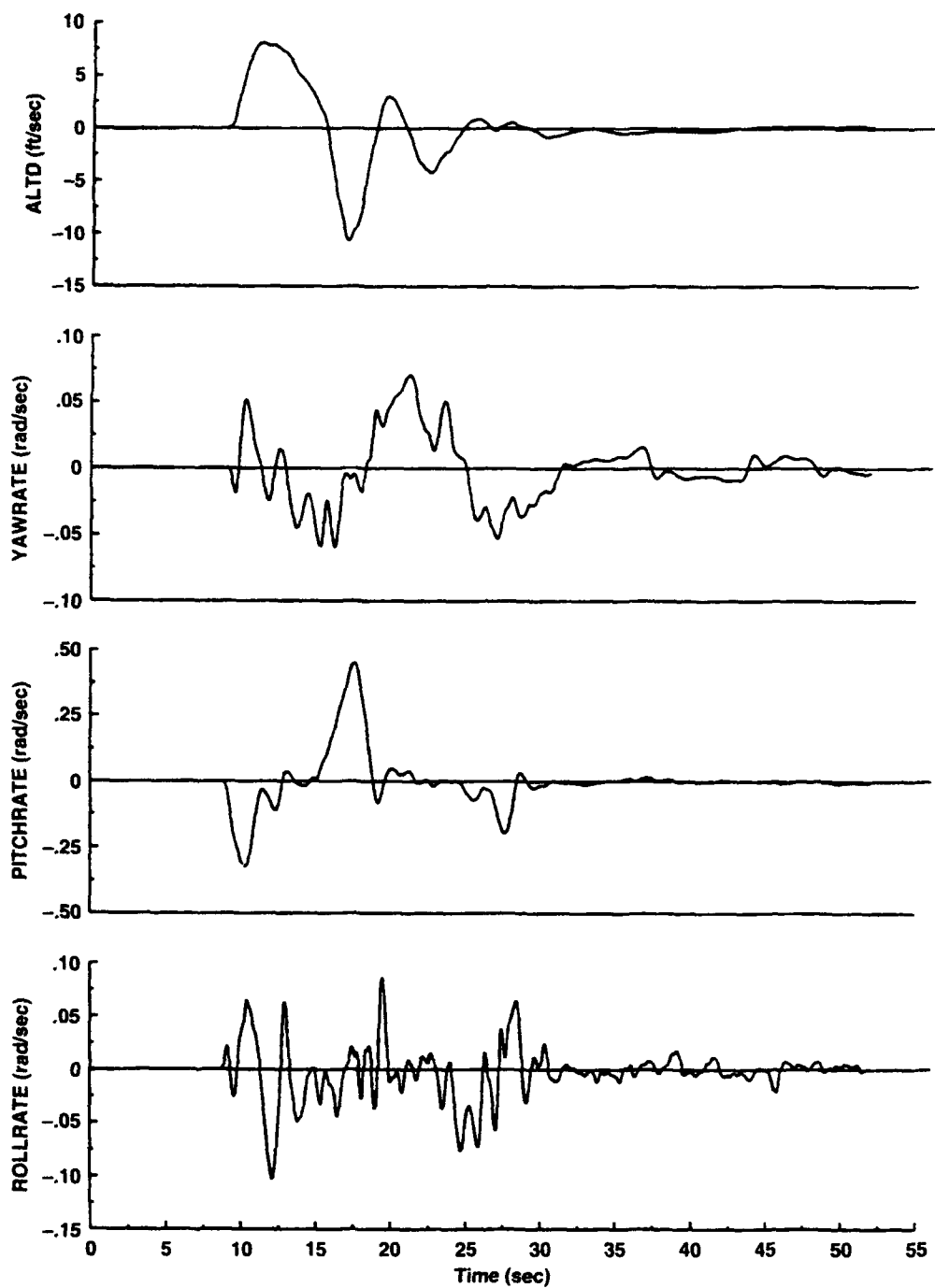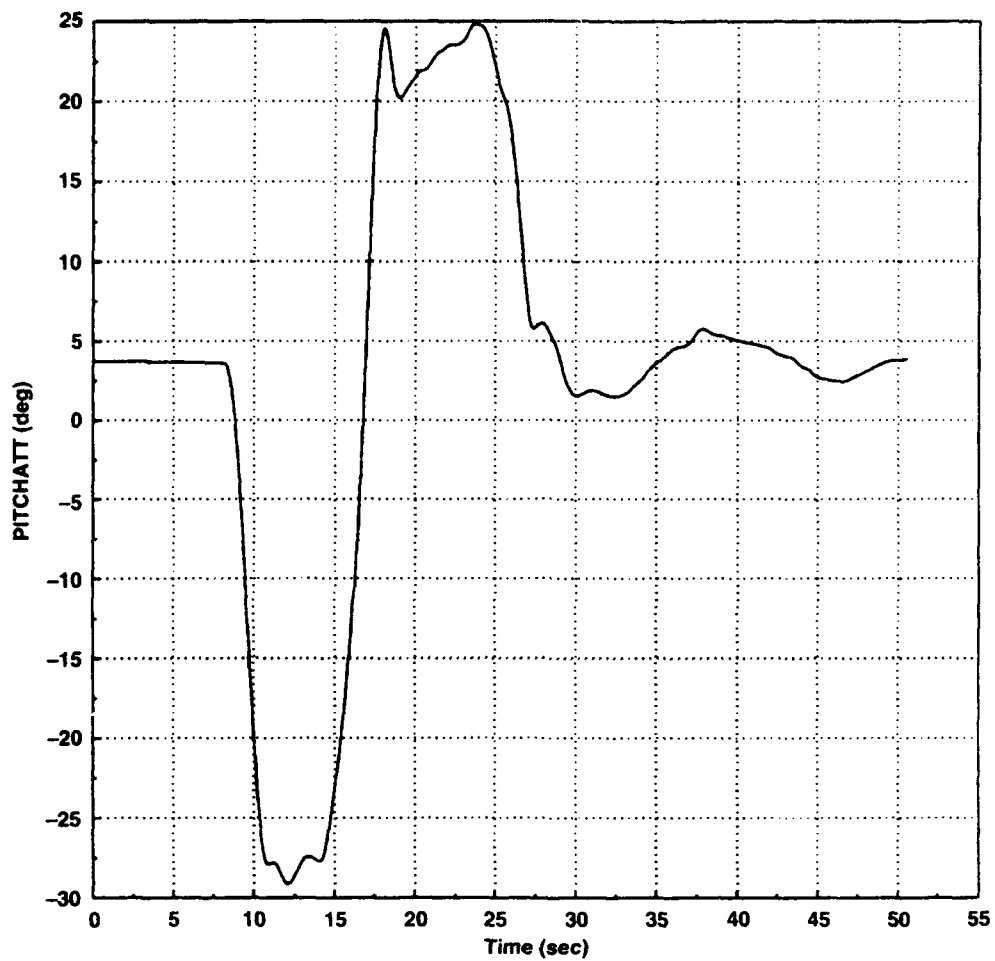Figure C-14. Side-step time history data for simulator (Pilot 5) (Continued).
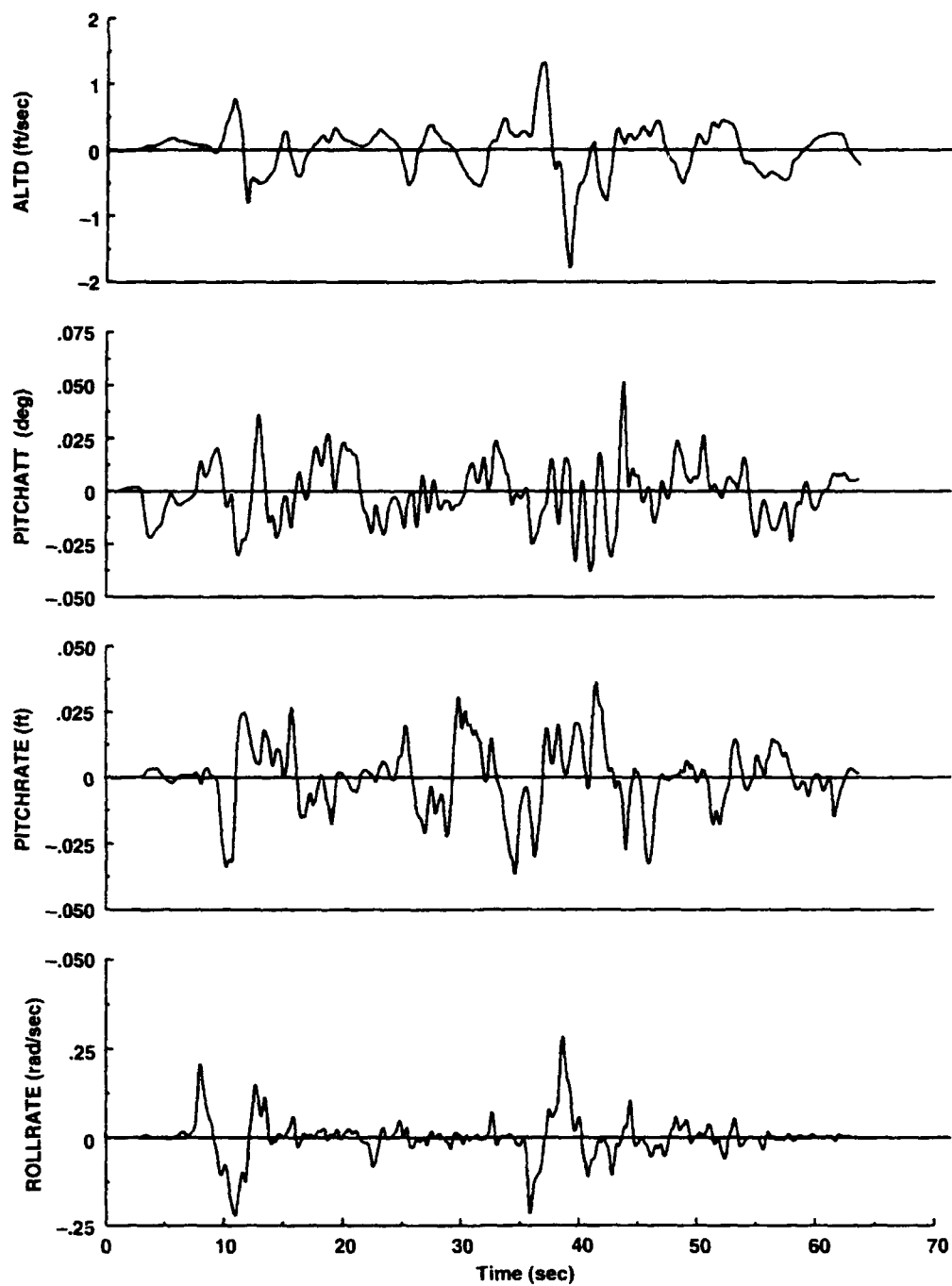
Figure C-14. Side-step time history data for simulator (Pilot 5) (Continued).
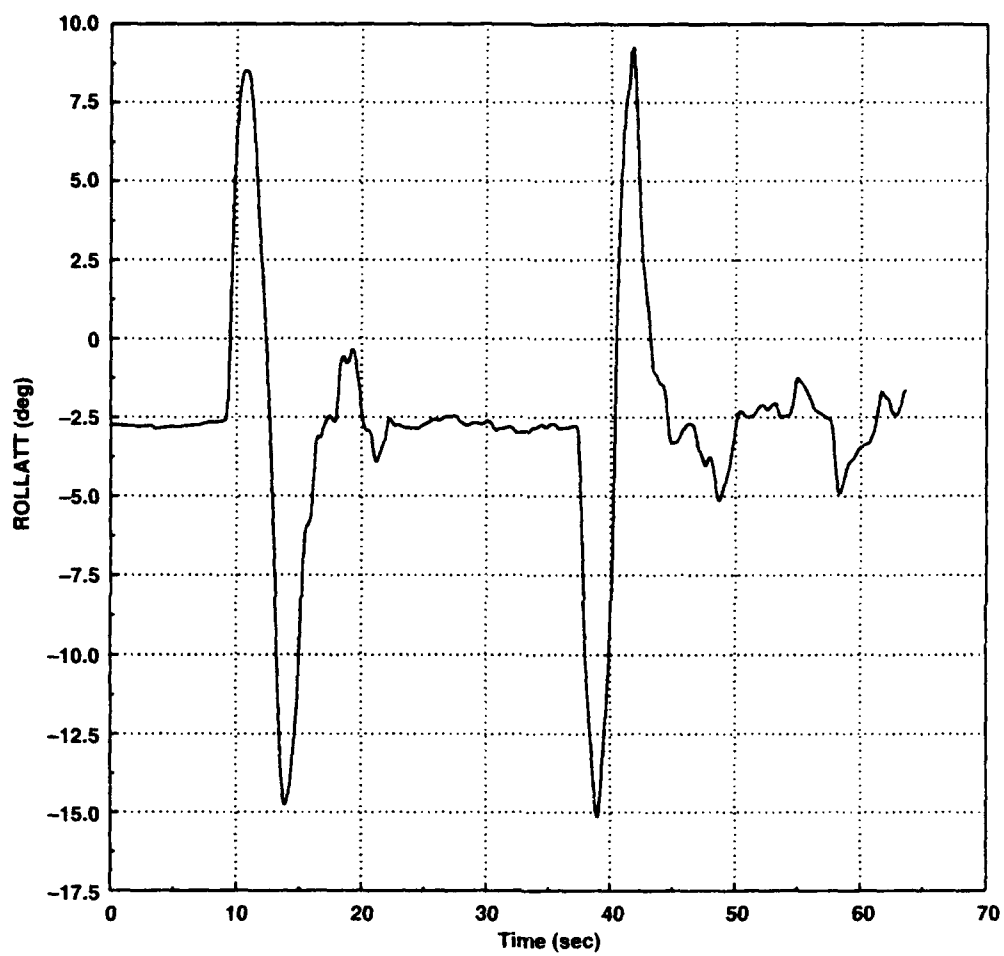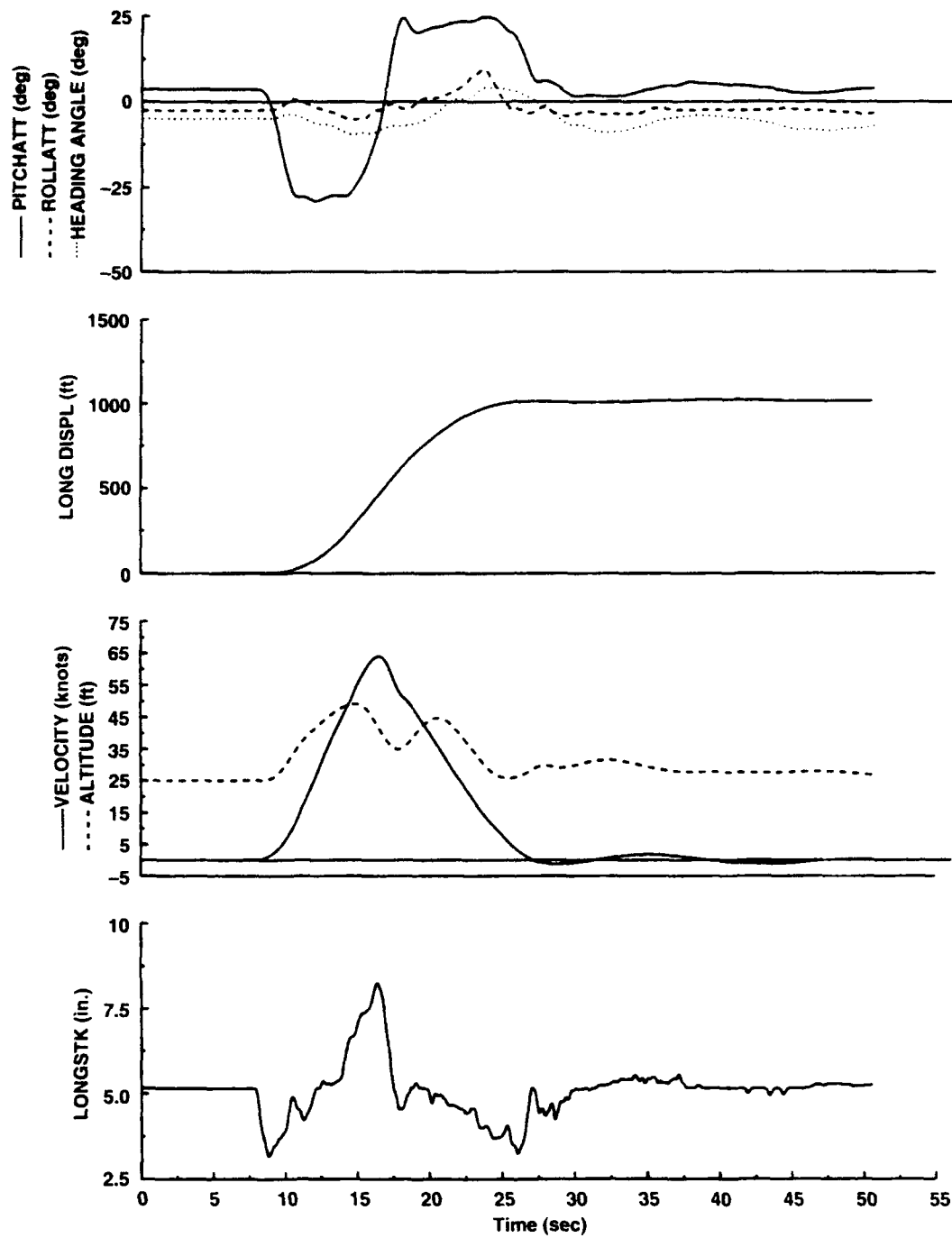
Figure C-14. Side-step time history data for simulator (Pilot 5) (Continued).

Figure C-14. Side-step time history data for simulator (Pilot 5) (Continued).
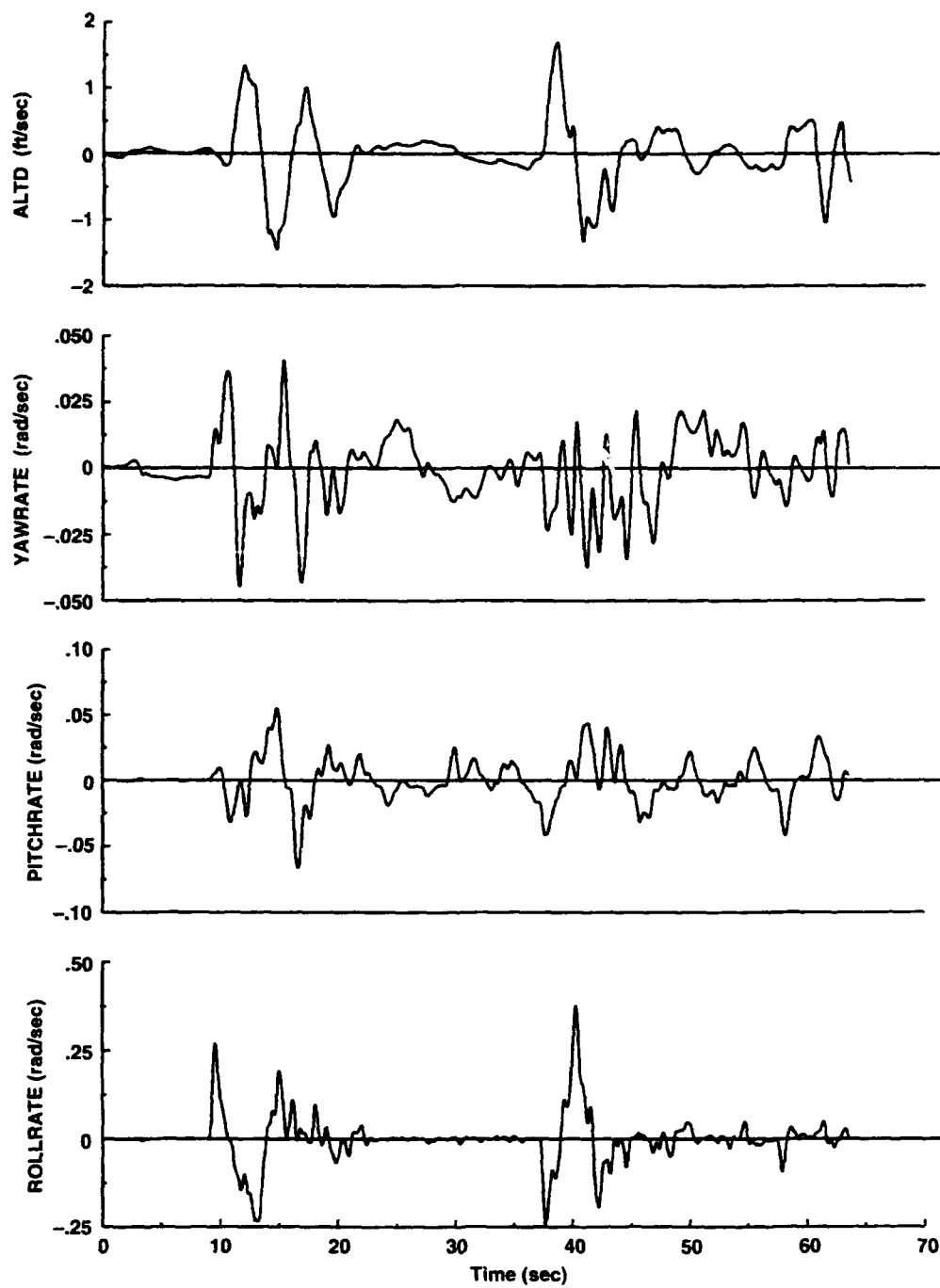
Figure C-14. Side-step time history data for simulator (Pilot 5) (Concluded).
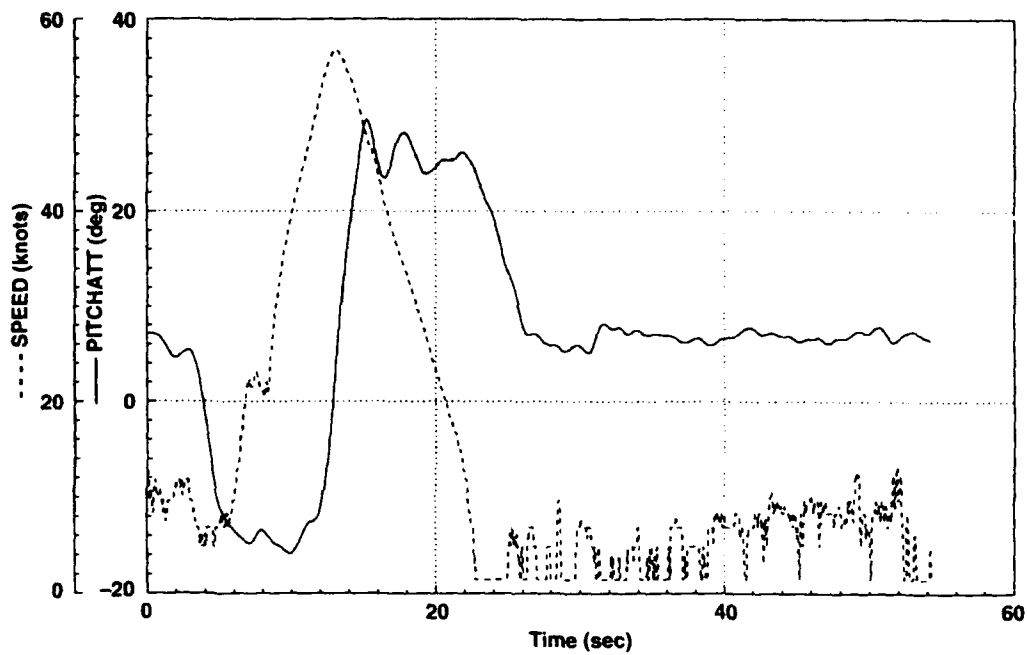
Figure C-15. Dash/quick-stop time history data for flight (Pilot 1).

Figure C-15. Dash/quick-stop time history data for flight (Pilot 1) (Continued).
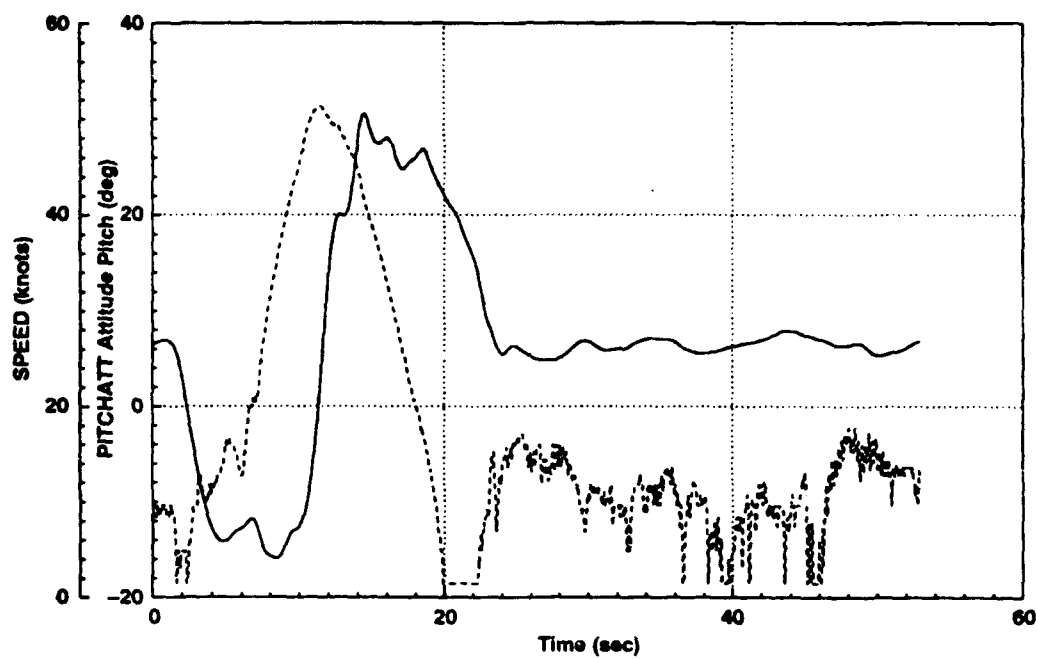
Figure C-15. Dash/quick-stop time history data for flight (Pilot 1) (Continued).

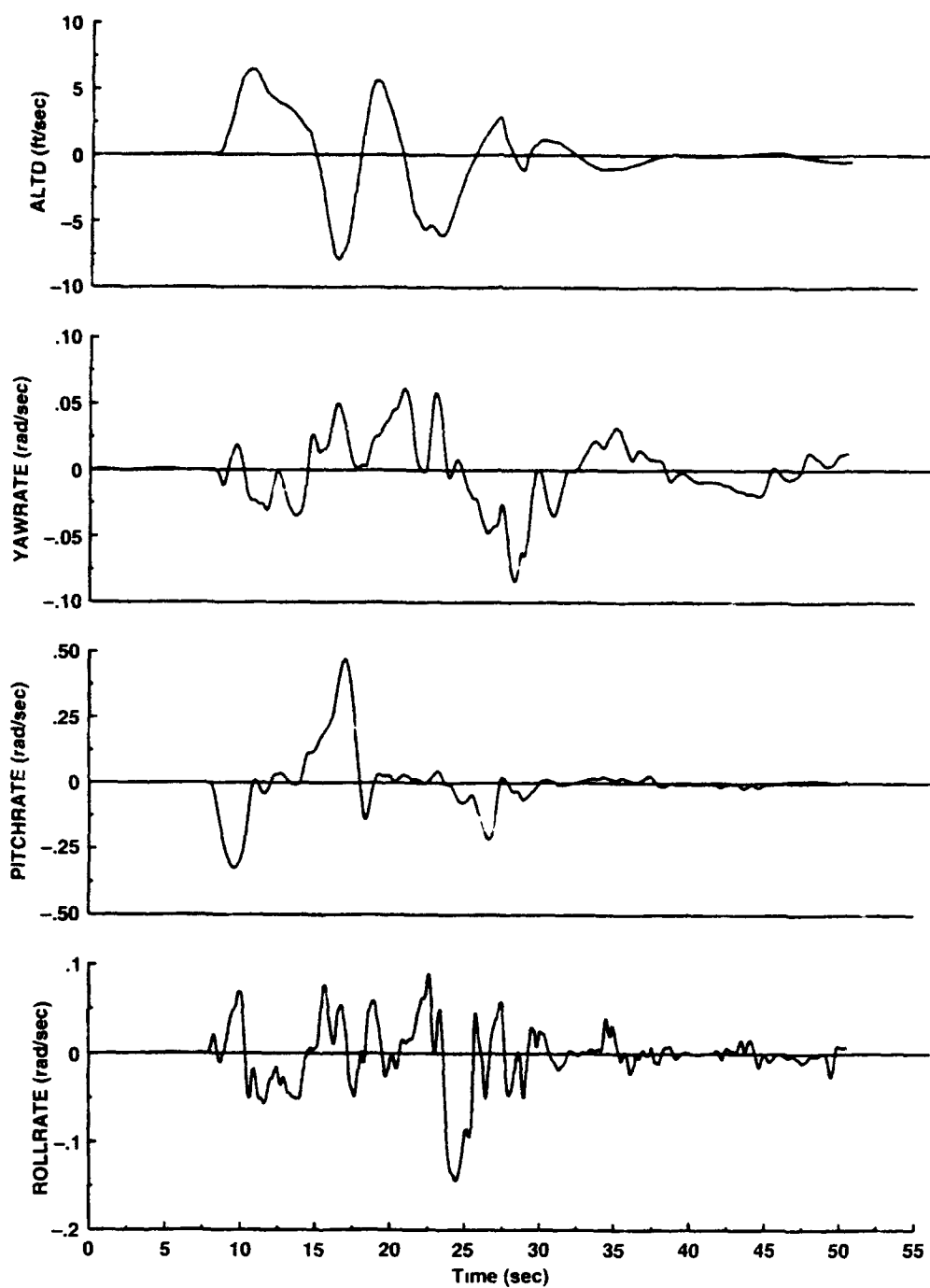Figure C-15. Dash/quick-stop time history data for flight (Pilot 1) (Continued).

Figure C-15. Dash/quick-stop time history data for flight (Pilot 1) (Continued).

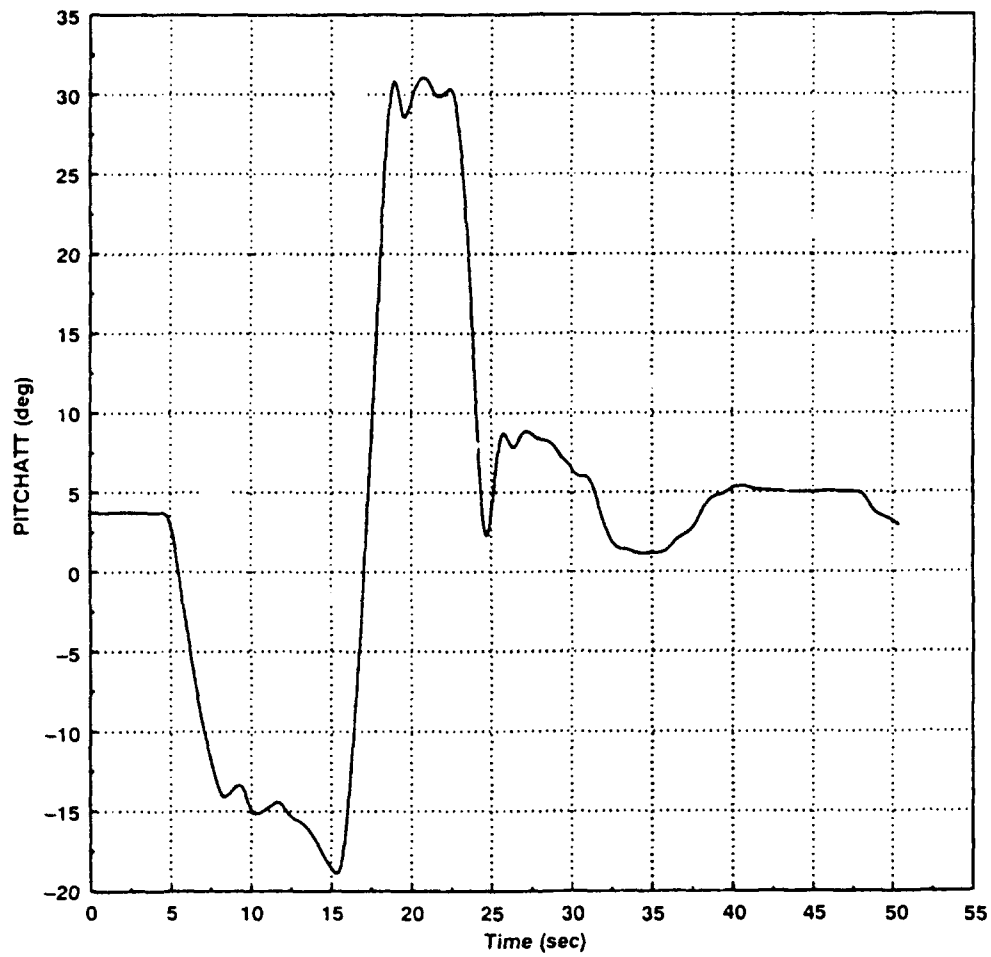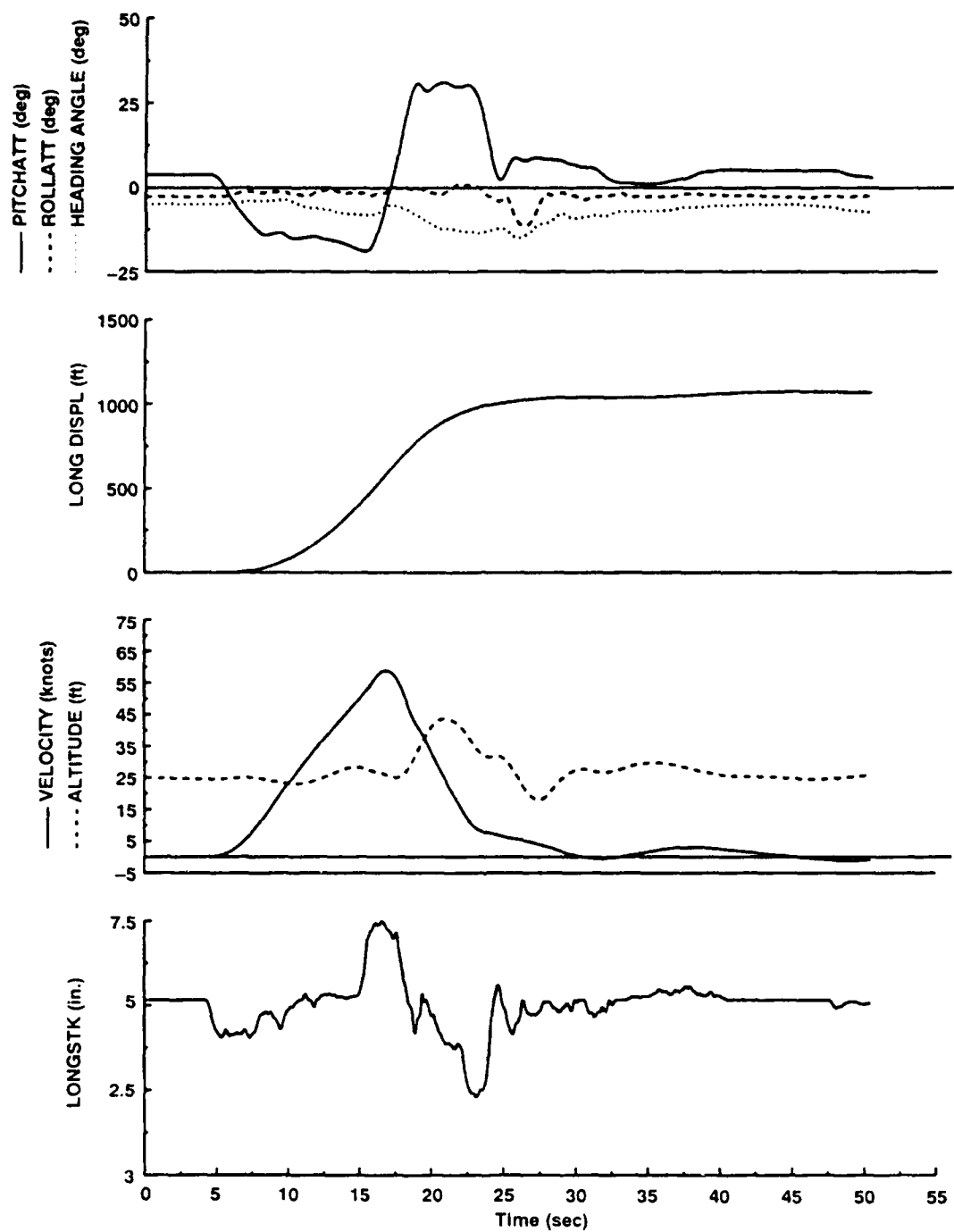Figure C-15. Dash/quick-stop time history data for flight (Pilot 1) (Concluded).
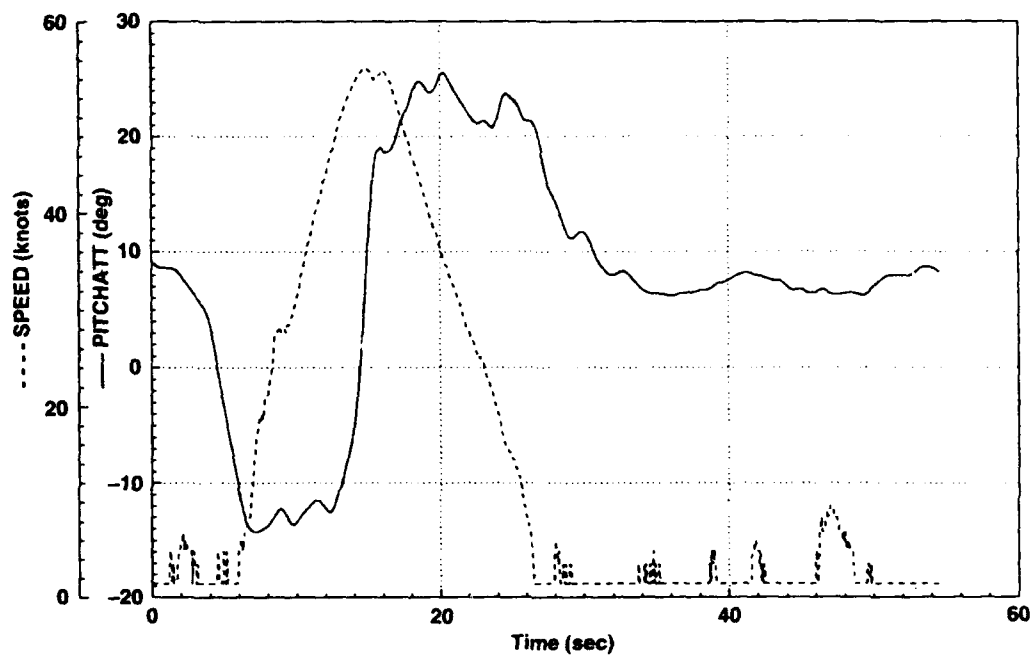
Figure C-16. Dash/quick-stop time history data for flight (Pilot 2).
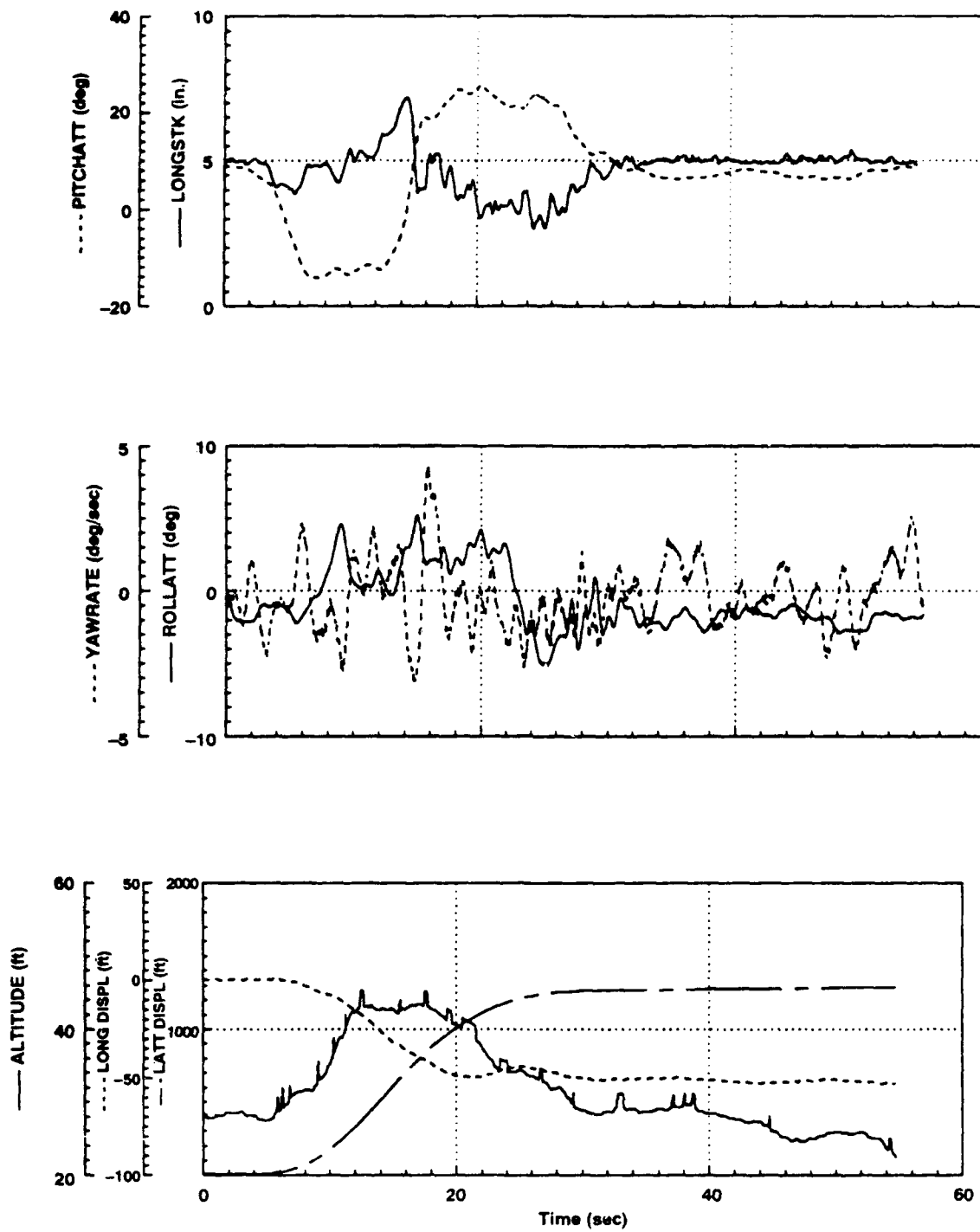
Figure C-16. Dash/quick-stop time history data for flight (Pilot 2) (Continued).
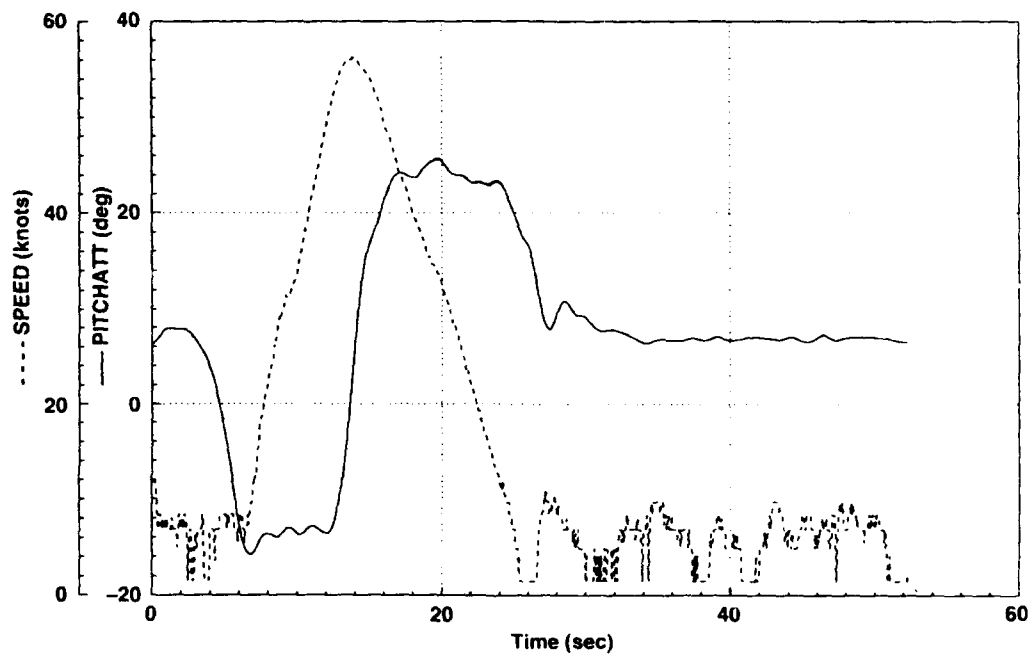
271

Figure C-16. Dash/quick-stop time history data for flight (Pilot 2) (Continued).
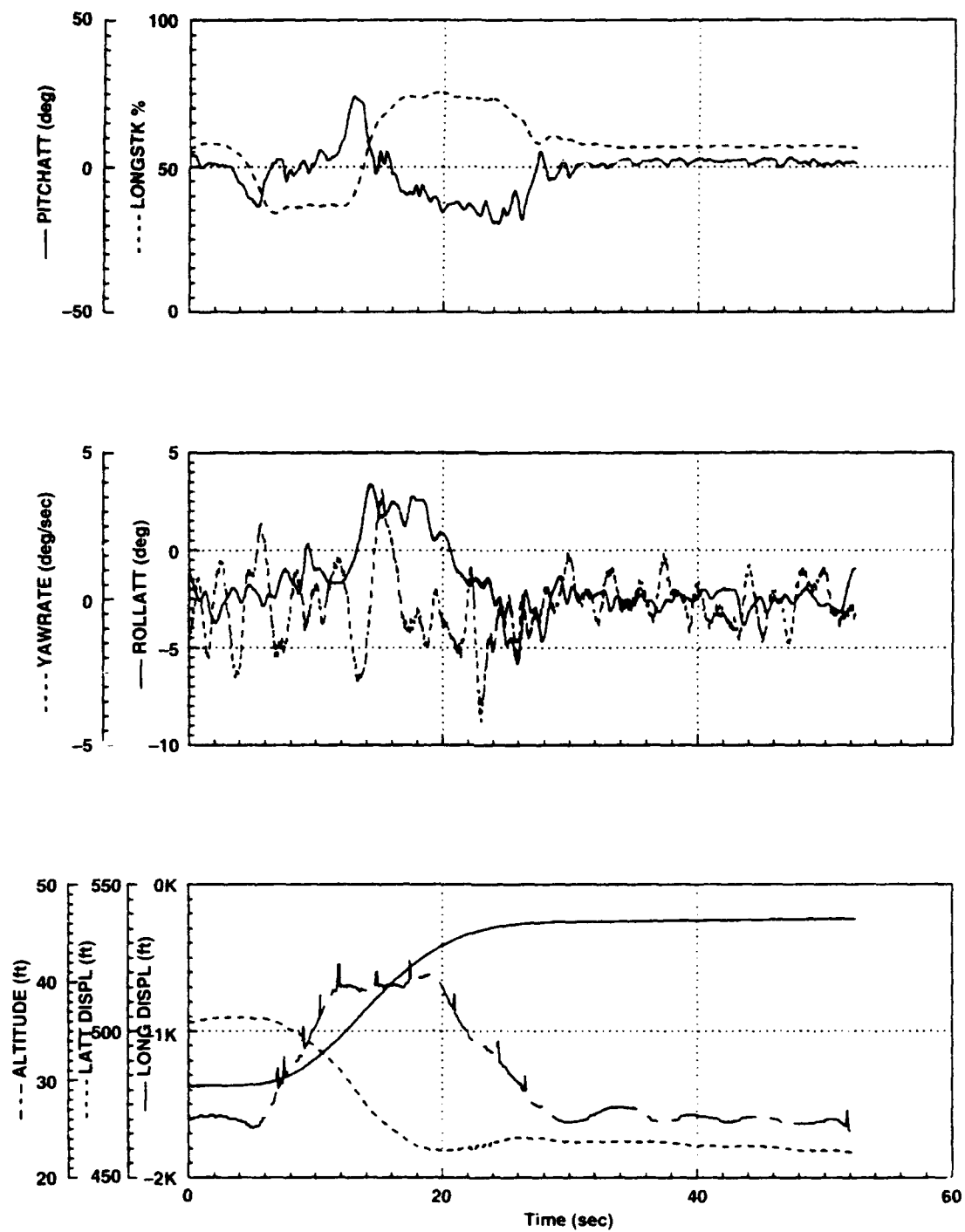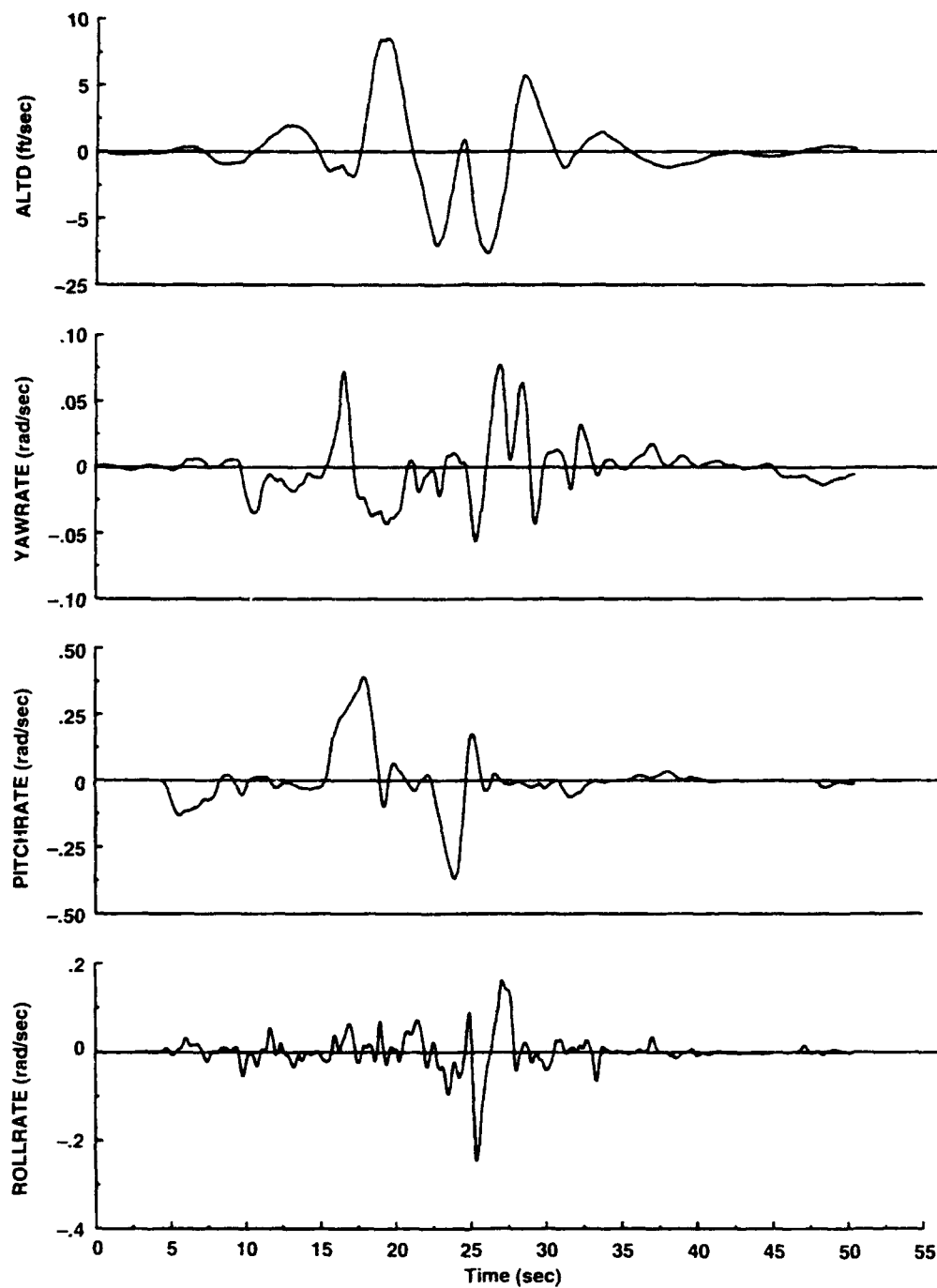
Figure C-16. Dash/quick-stop time history data for flight (Pilot 2) (Continued).
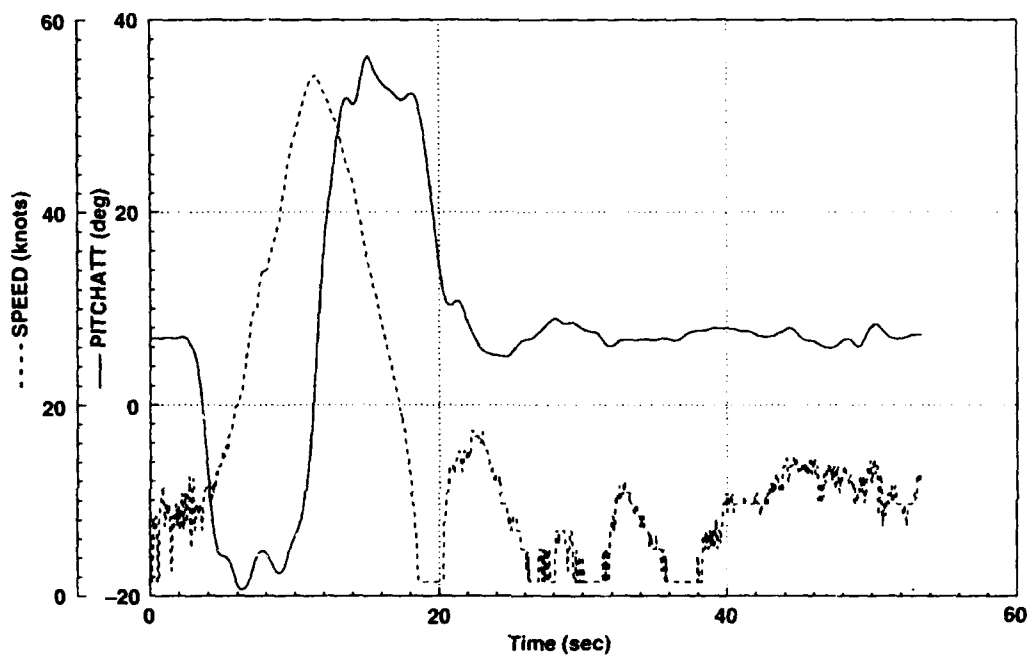
Figure C-16. Dash/quick-stop time history data for flight (Pilot 2) (Continued).
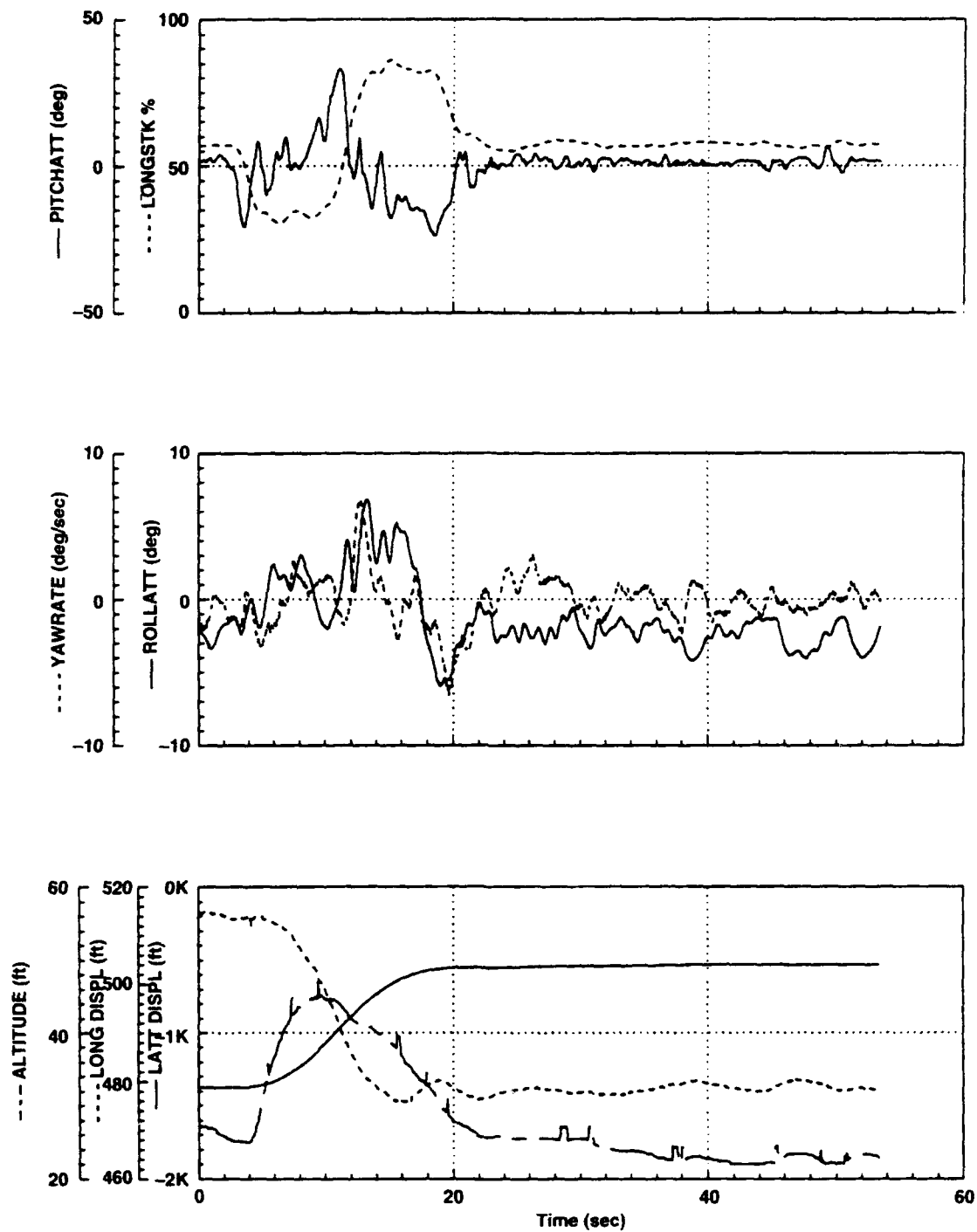
Figure C-16. Dash/quick-stop time history data for flight (Pilot 2) (Concluded).
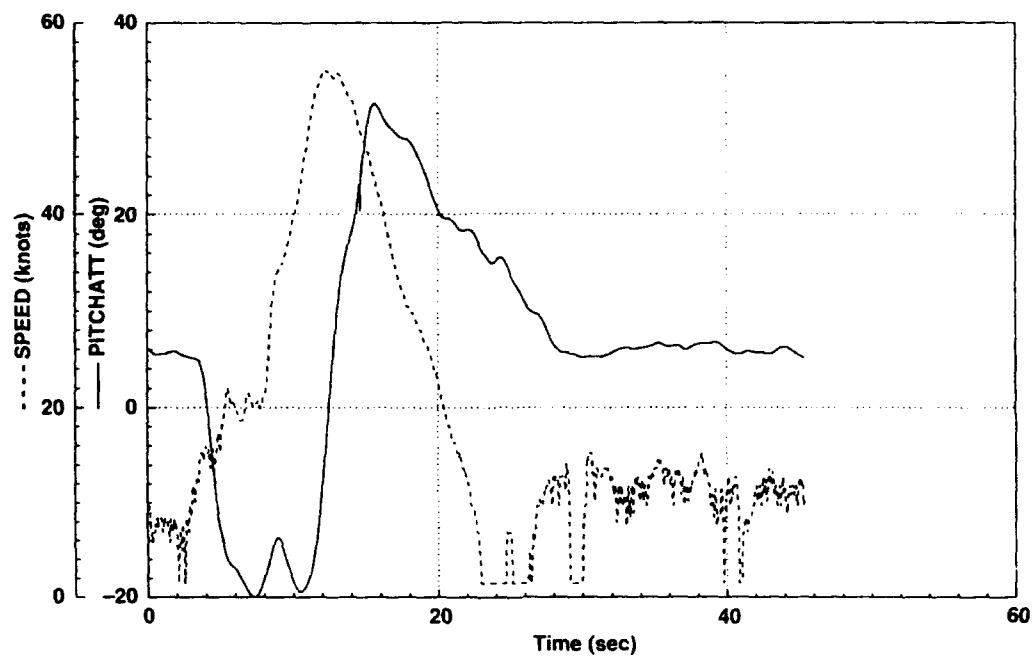
Figure C-17. Dash/quick-stop time history data for flight (Pilot 3).

Figure C-17. Dash/quick-stop time history data for flight (Pilot 3) (Continued).

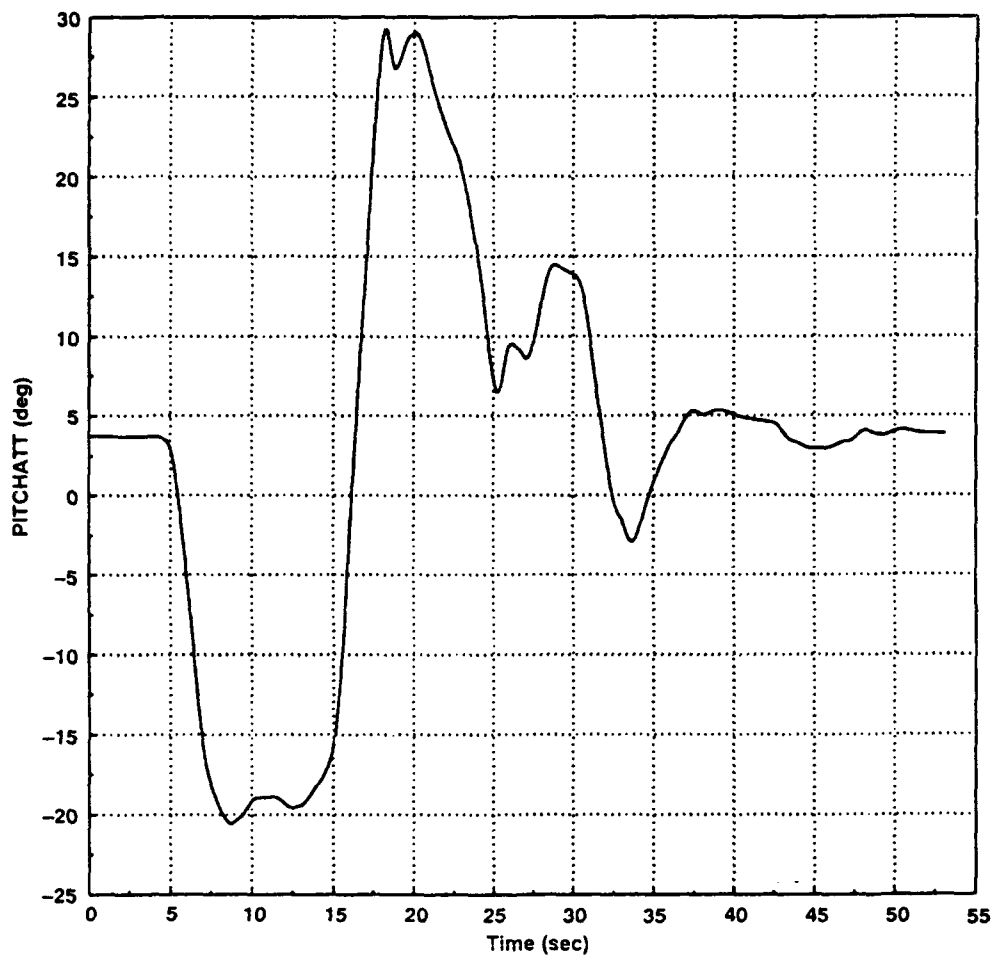Figure C-17. Dash/quick-stop time history data for flight (Pilot 3) (Continued).

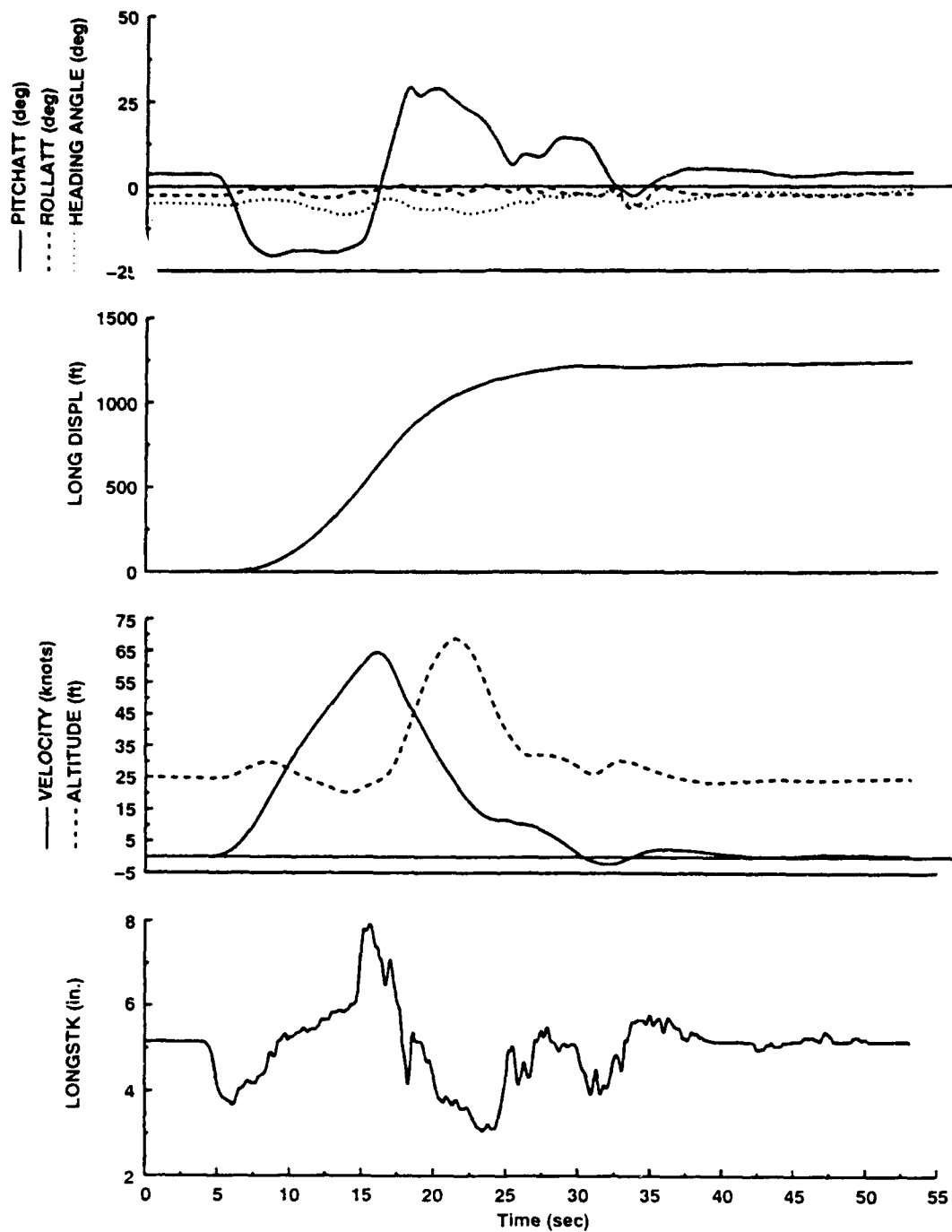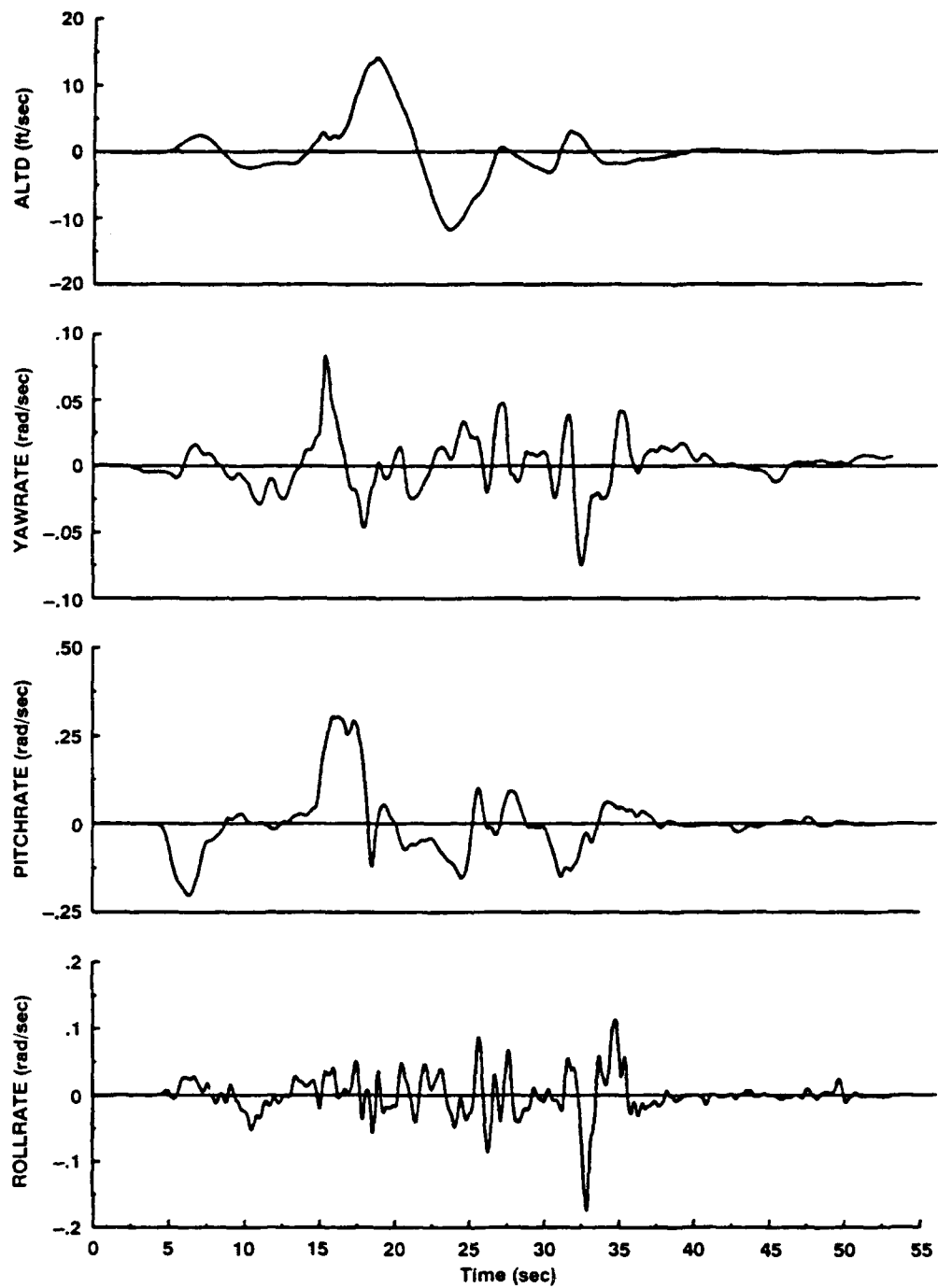Figure C-17. Dash/quick-stop time history data for flight (Pilot 3) (Continued).

Figure C-17. Dash/quick-stop time history data for flight (Pilot 3) (Continued).

Figure C-17. Dash/quick-stop time history data for flight (Pilot 3) (Concluded).

Figure C-18. Dash/quick-stop time history data for flight (Pilot 4).

Figure C-18. Dash/quick-stop time history data for flight (Pilot 4) (Continued).

Figure C-18. Dash/quick-stop time history data for flight (Pilot 4) (Continued).

Figure C-18. Dash/quick-stop time history data for flight (Pilot 4) (Continued).

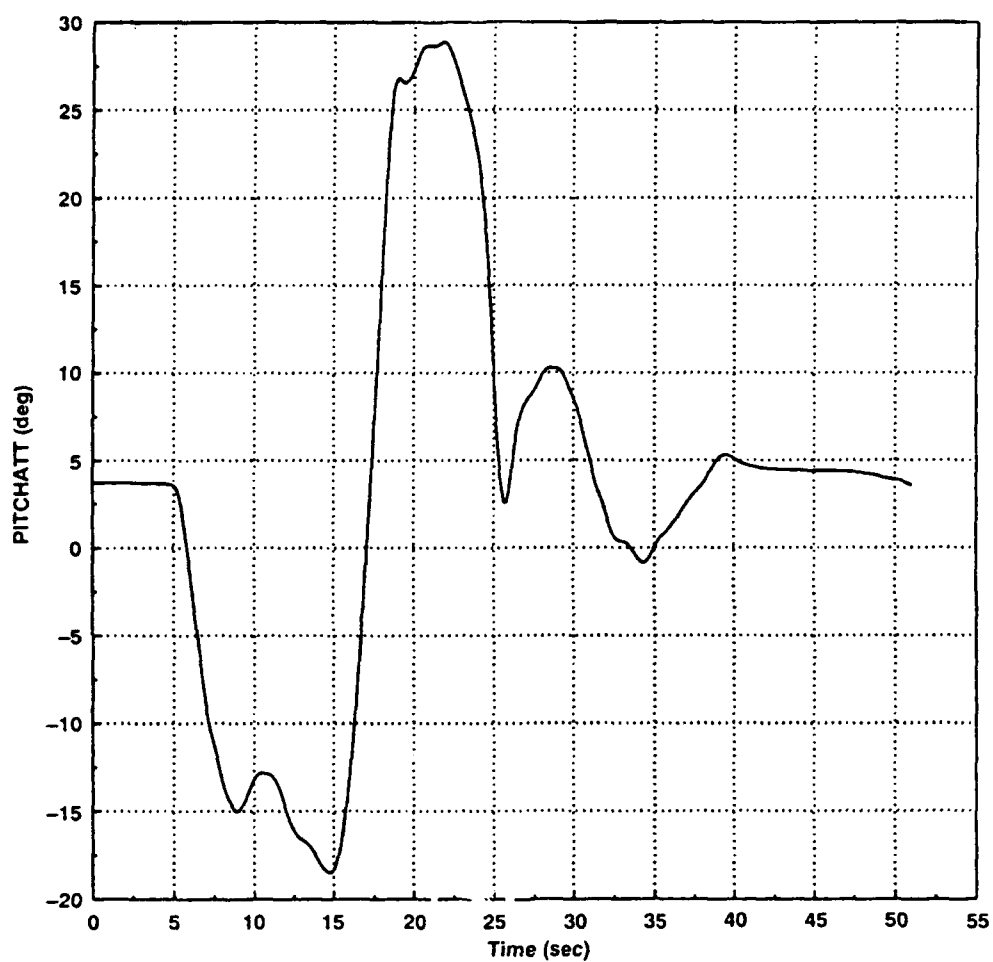Figure C-18. Dash/quick-stop time history data for flight (Pilot 4) (Continued).

Figure C-18. Dash/quick-stop time history data for flight (Pilot 4) (Concluded).

Figure C-19. Dash/quick-stop time history data for simulator (Pilot 2).
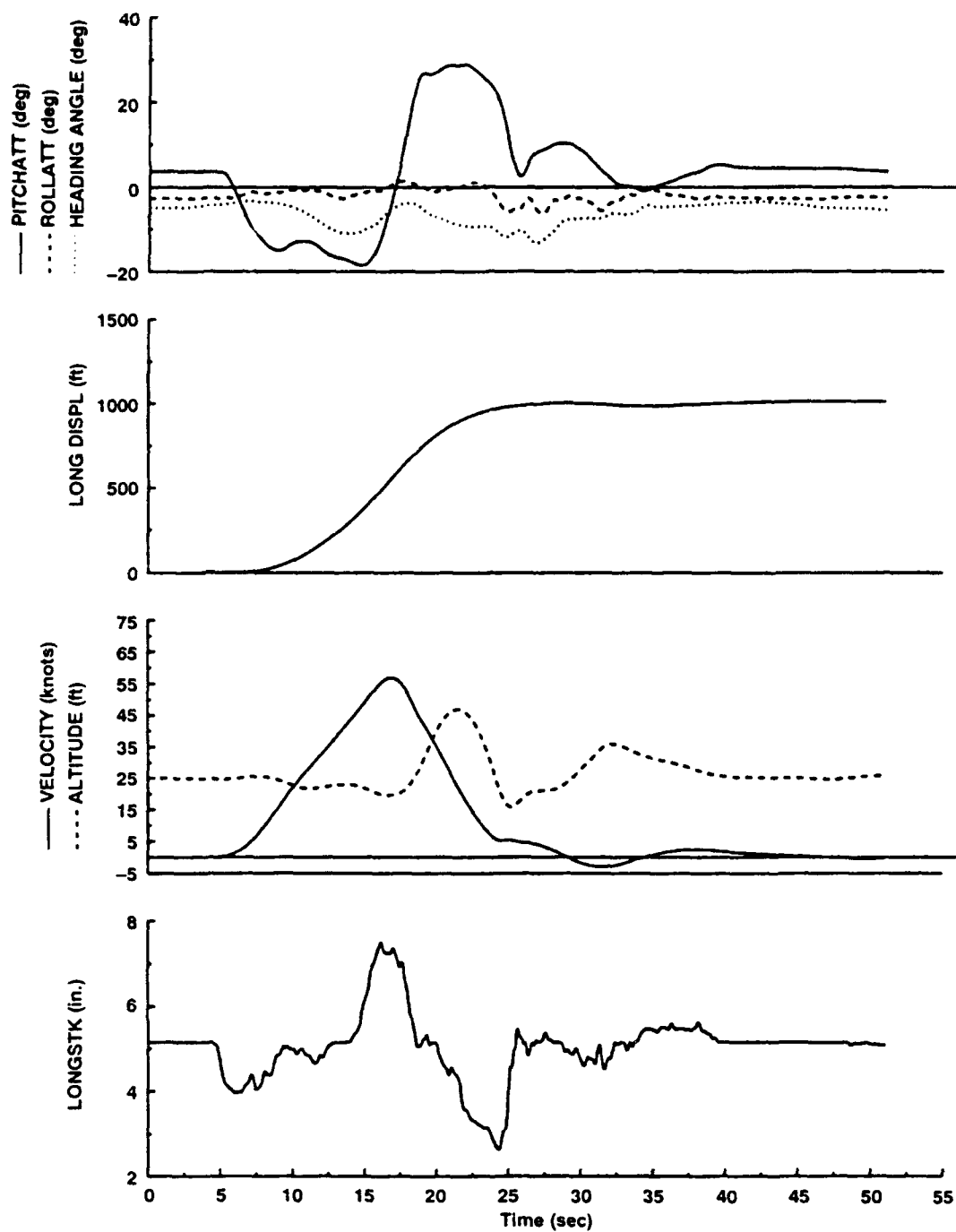
Figure C-12. Dash/quick-stop time history data for simulator (Pilot 2) (Continued).

289

Figure C-19. Dash/quick-stop time history data for simulator (Pilot 2) (Continued).

Figure C-19. Dash/quick-stop time history data for simulator (Pilot 2) (Continued).
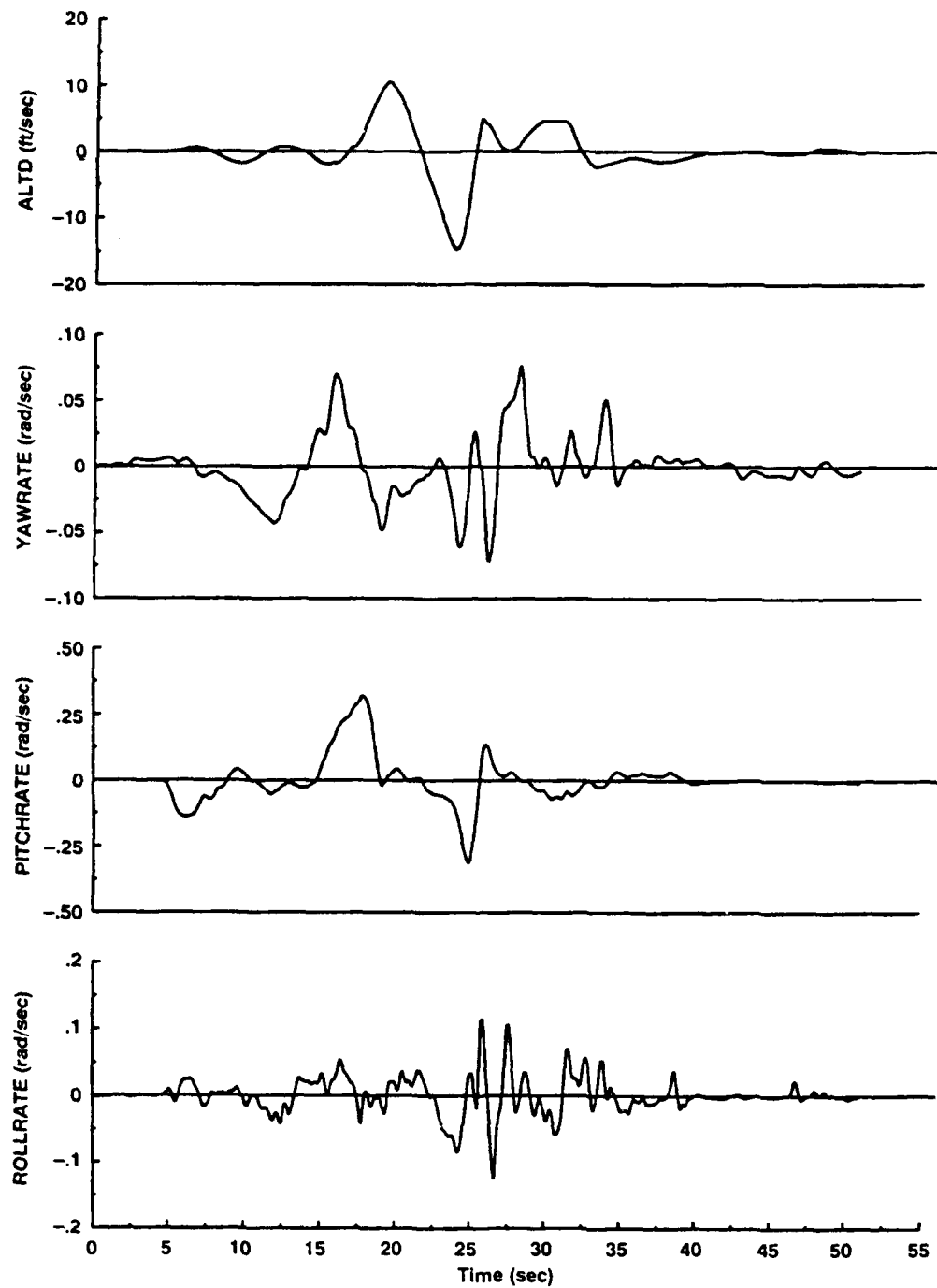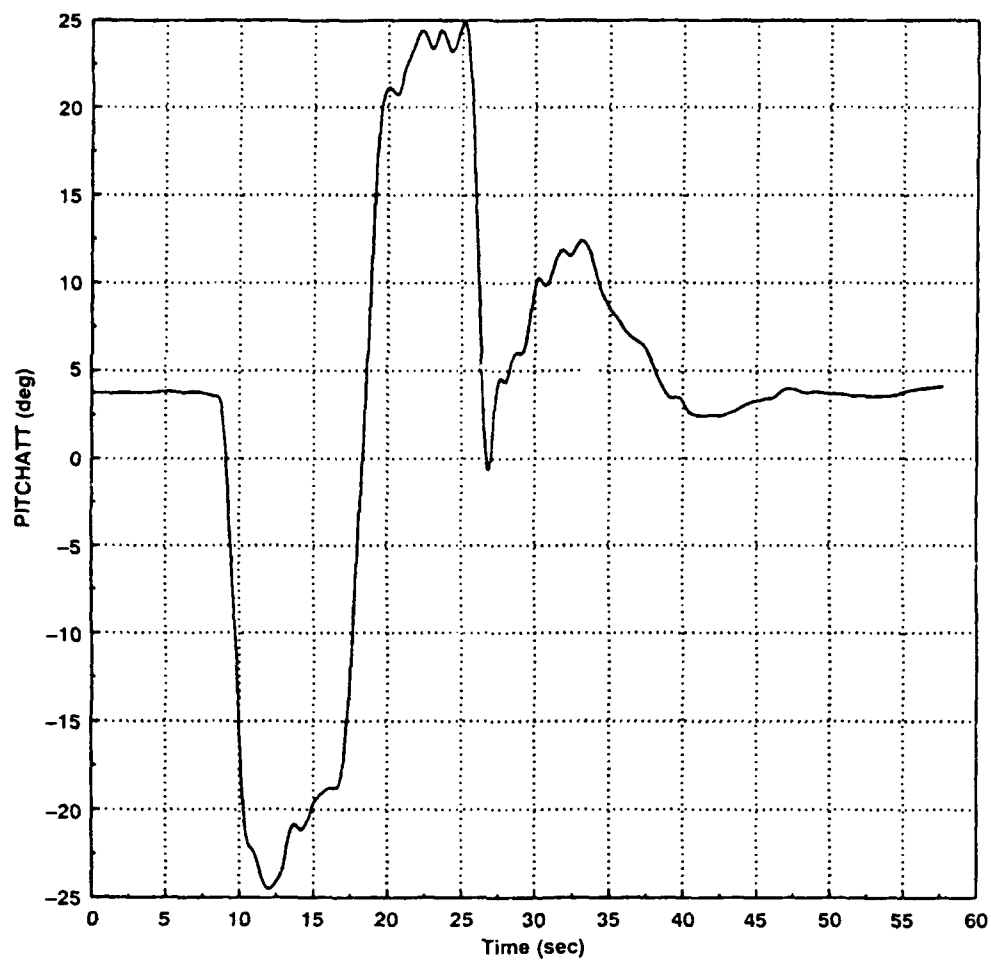
Figure C-19. Dash/quick-stop time history data for simulator (Pilot 2) (Continued).

292

Figure C-19. Dash/quick-stop time history data for simulator (Pilot 2) (Continued).

293

Figure C-19. Dash/quick-stop time history data for simulator (Pilot 2) (Continued).

294

Figure C-19. Dash/quick-stop time history data for simulator (Pilot 2) (Continued).

295

Figure C-19. Dash/quick-stop time history data for simulator (Pilot 2) (Concluded).

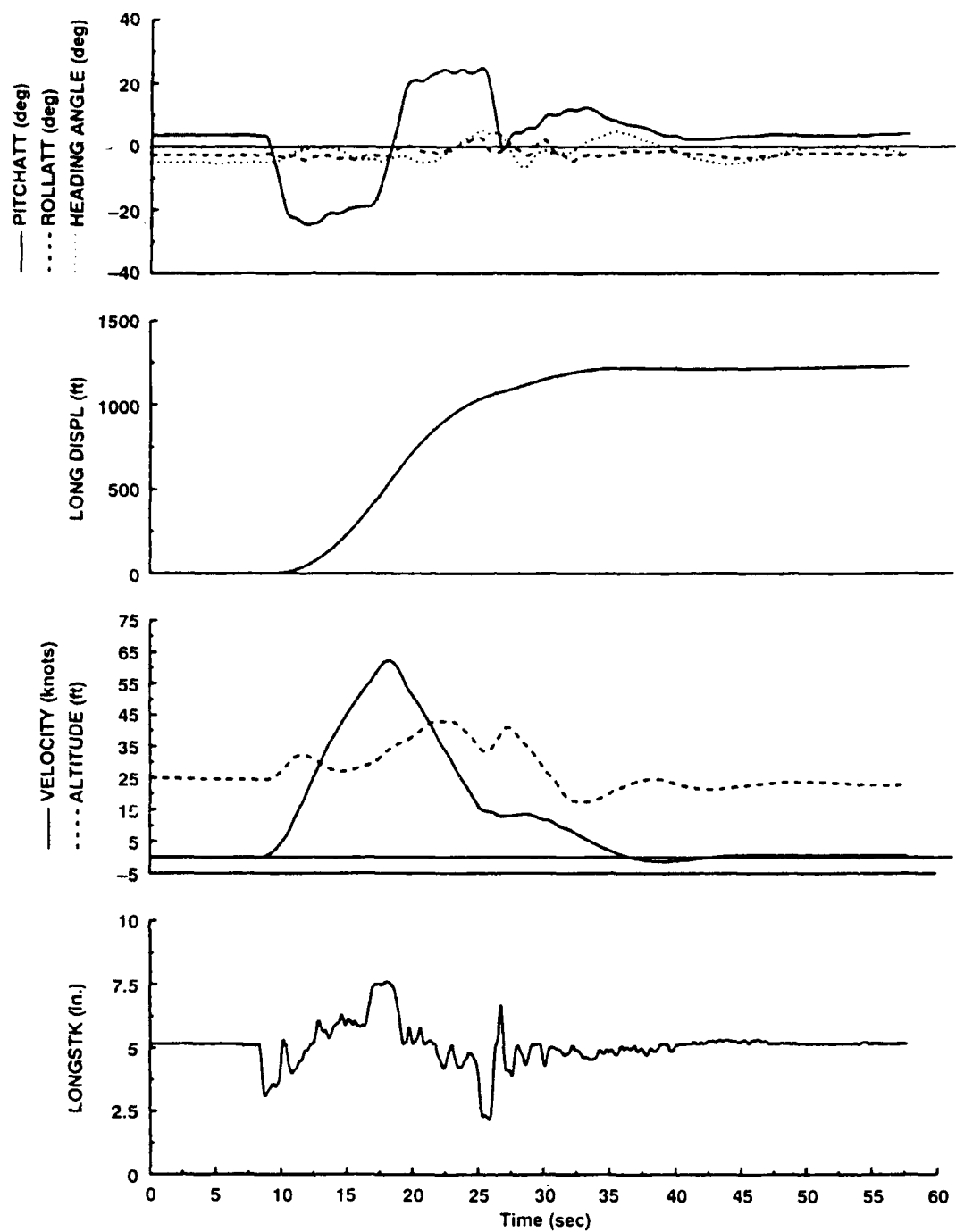Figure C-20. Dash/quick-stop time history data for simulator (Pilot 4).

Figure C-20. Dash/quick-stop time history data for simulator (Pilot 4) (Continued).
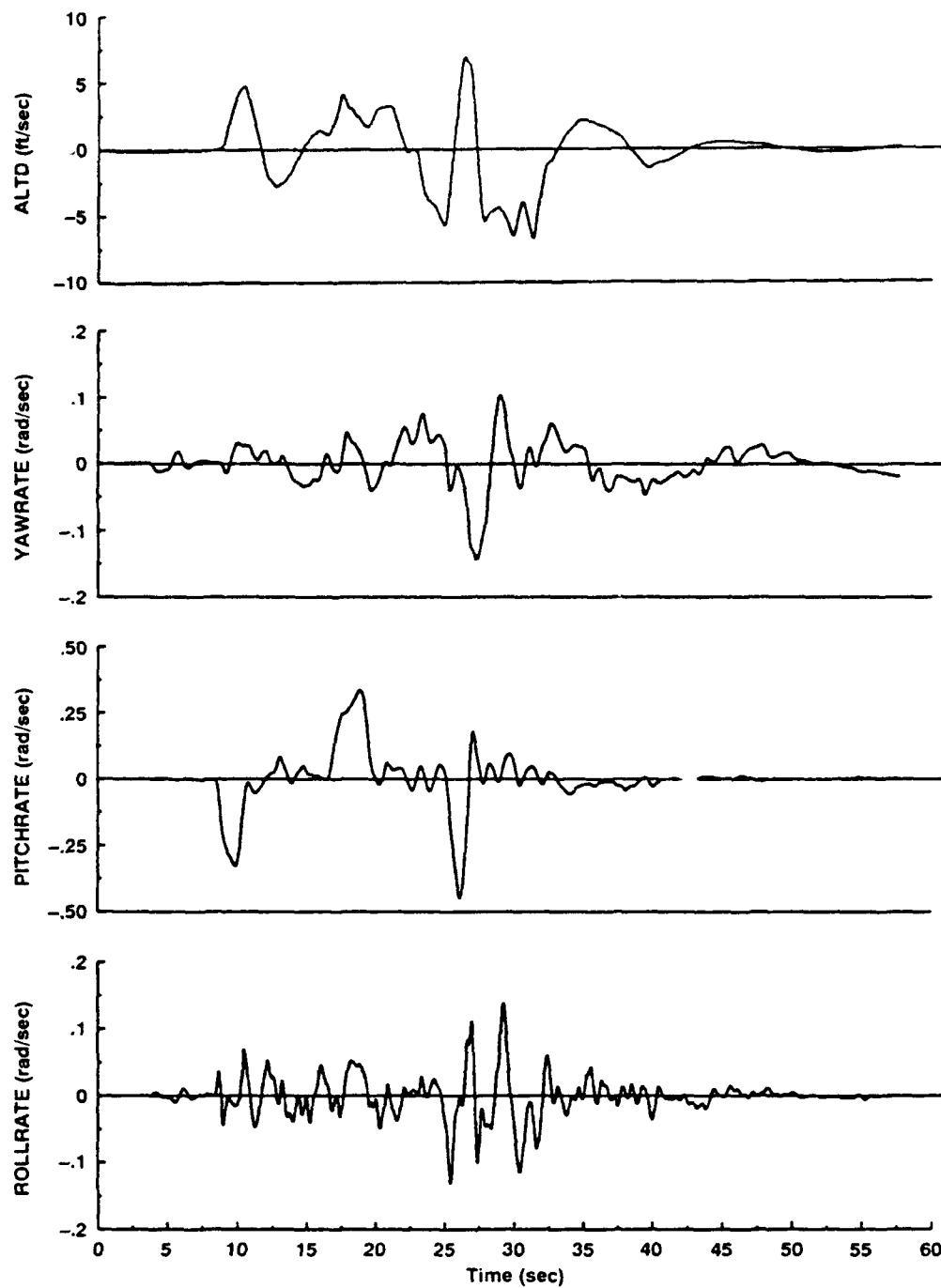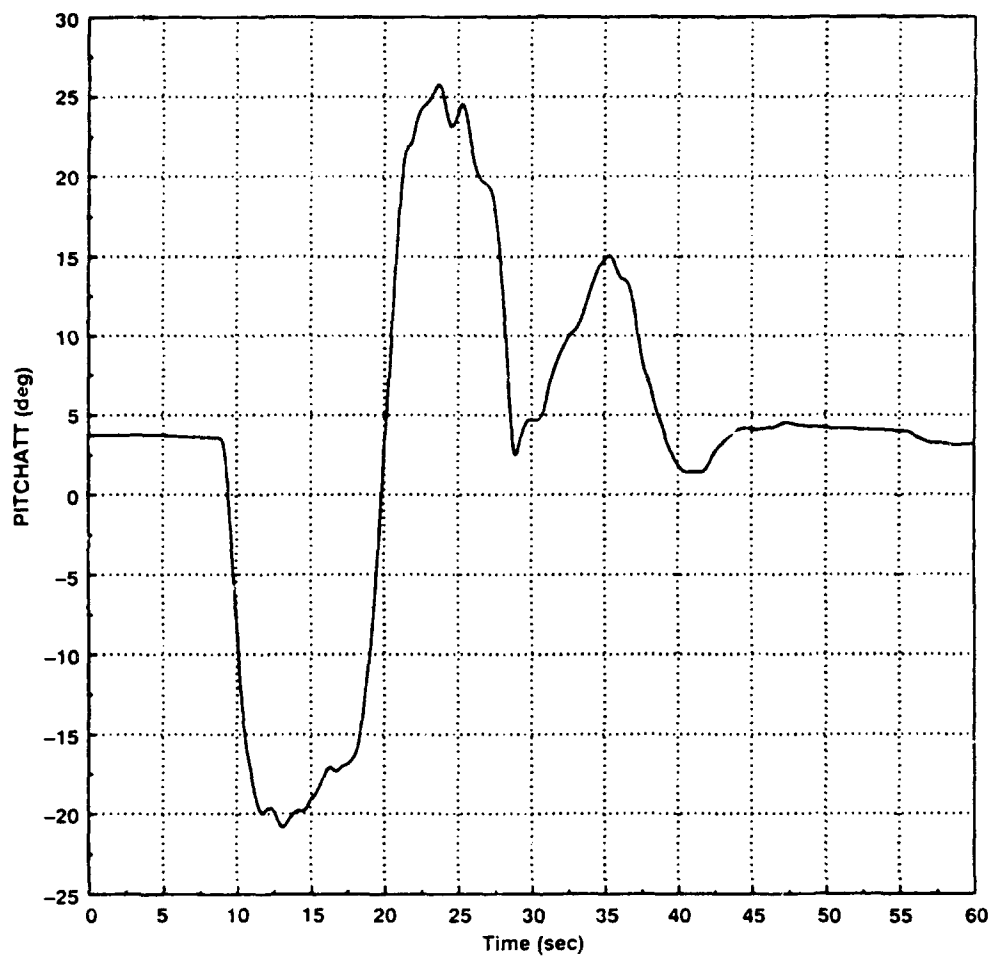
298

Figure C-20. Dash/quick-stop time history data for simulator (Pilot 4) (Continued).

Figure C-20. Dash/quick-stop time history data for simulator (Pilot 4) (Continued).
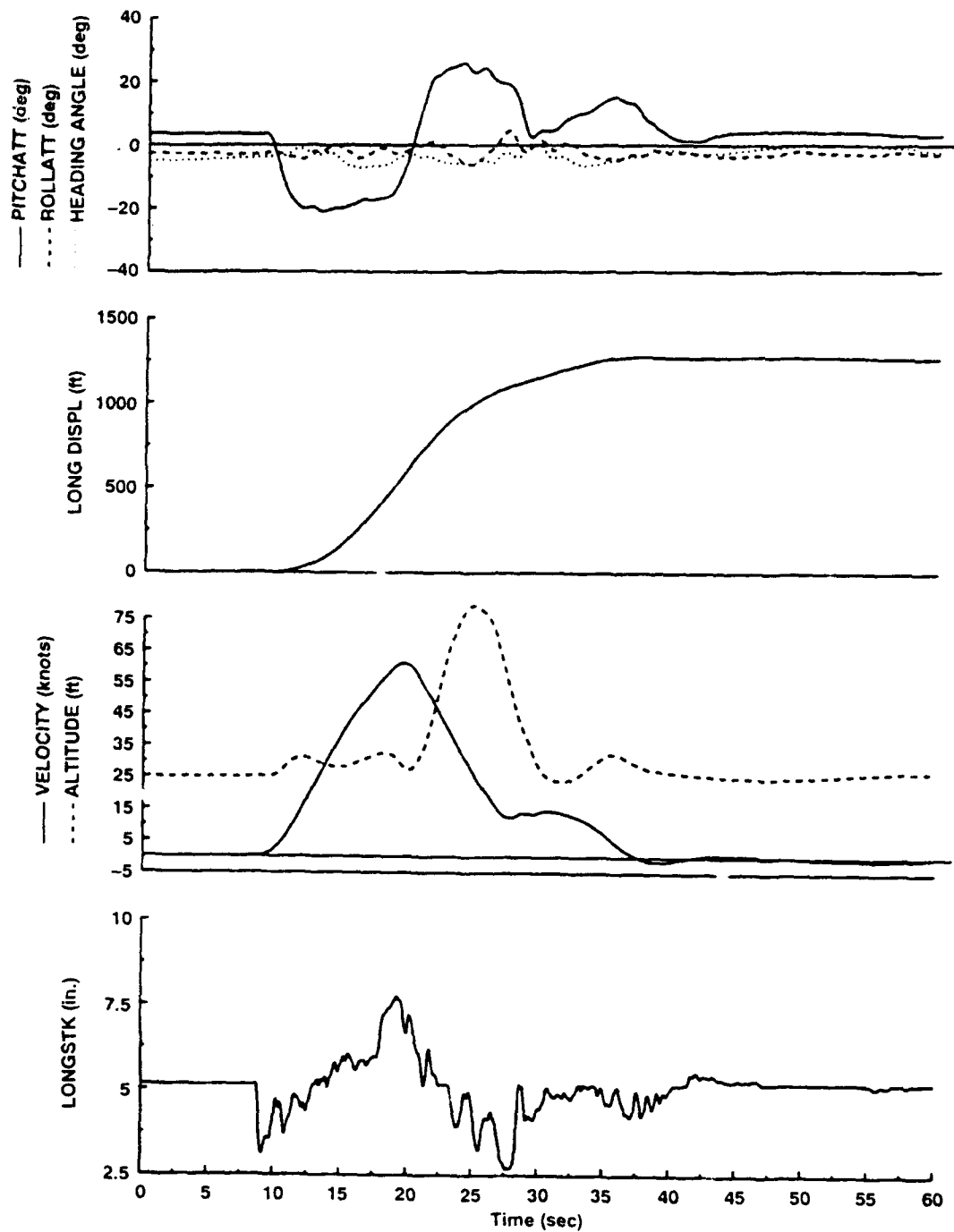
300

Figure C-20. Dash/quick-stop time history data for simulator (Pilot 4) (Continued).

Figure C-20. Dash/quick-stop time history data for simulator (Pilot 4) (Continued).

Figure C-20. Dash/quick-stop time history data for simulator (Pilot 4) (Continued).
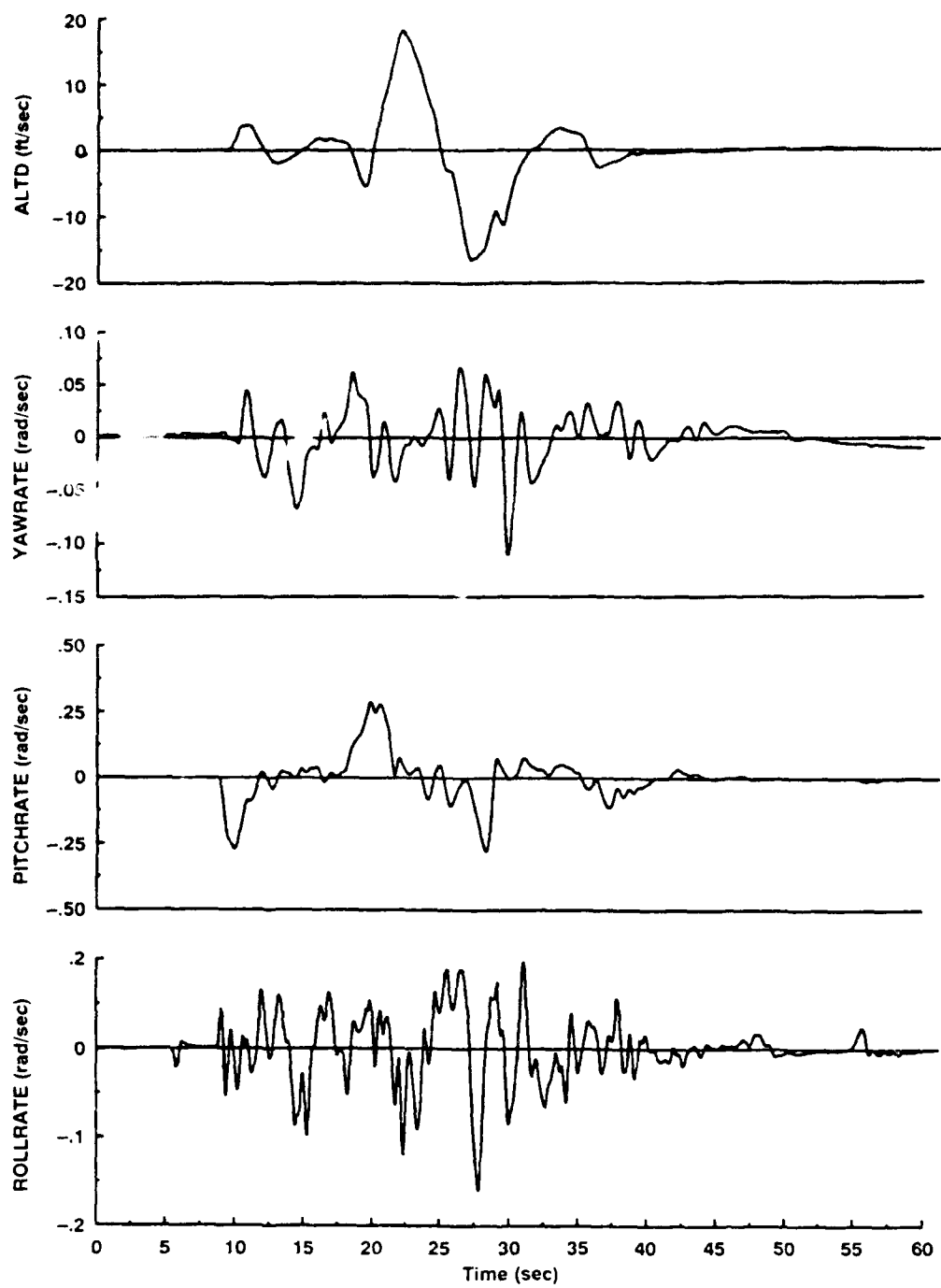
Figure C-20. Dash/quick-stop time history data for simulator (Pilot 4) (Continued).

Figure C-20. Dash/quick-stop time history data for simulator (Pilot 4) (Concluded).

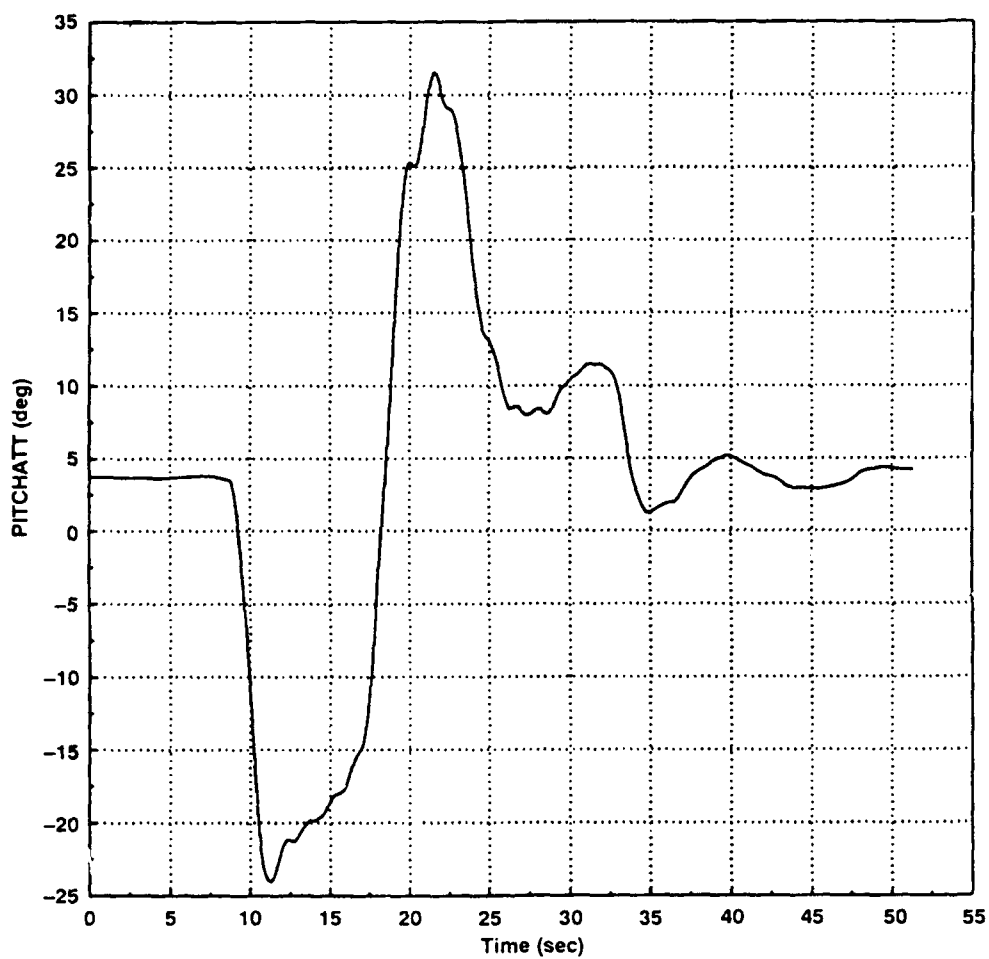Figure C-21. Dash/quick-stop time history data for simulator (Pilot 5).

Figure C-21. Dash/quick-stop time history data for simulator (Pilot 5) (Continued).

Figure C-21. Dash/quick-stop time history data for simulator (Pilot 5) (Continued).
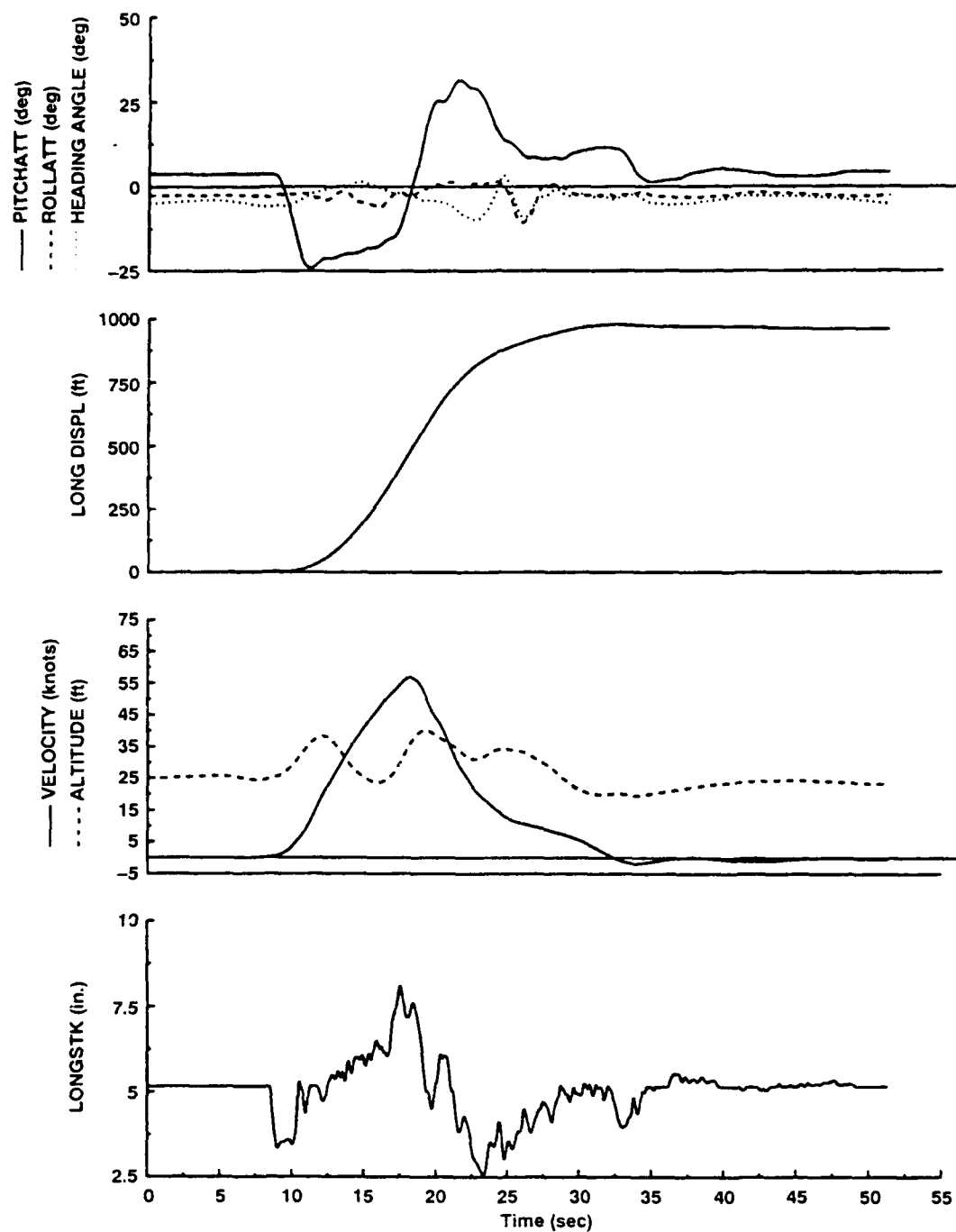
Figure C-21. Dash/quick-stop time history data for simulator (Pilot 5) (Continued).

Figure C-21. Dash/quick-stop time history data for simulator (Pilot 5) (Continued).

Figure C-21. Dash/quick-stop time history data for simulator (Pilot 5) (Continued).

Figure C-21. Dash/quick-stop time history data for simulator (Pilot 5) (Continued).

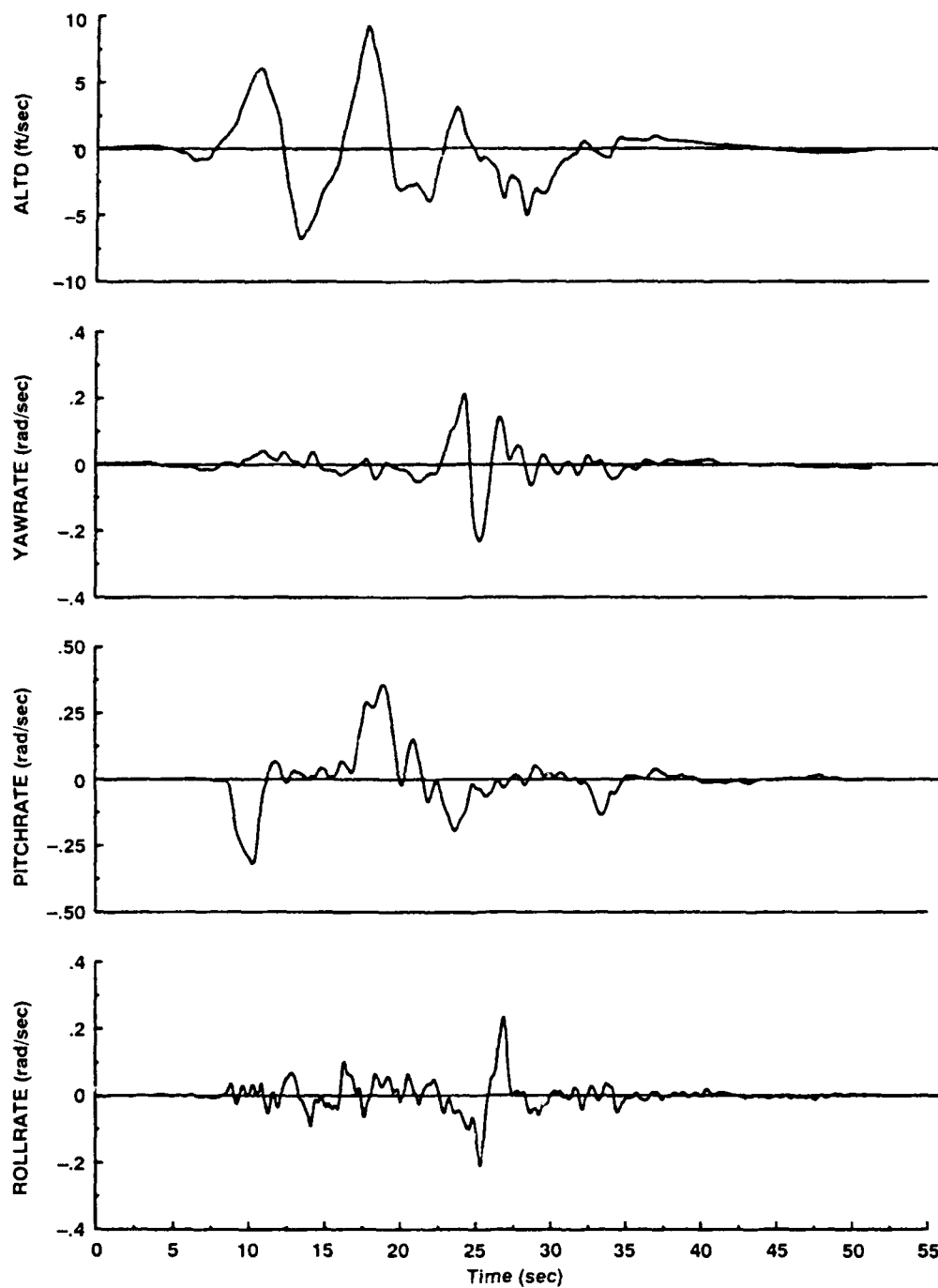Figure C-21. Dash/quick-stop time history data for simulator (Pilot 5) (Continued).

Figure C-21. Dash/quick-stop time history data for simulator (Pilot 5) (Concluded).

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1993	Technical Memorandum

4. TITLE AND SUBTITLE

Fidelity Assessment of a UH-60A Simulation on the NASA Ames Vertical Motion Simulator

5. FUNDING NUMBERS

505-59-52

Army funding numbers:
Program Element Number   62211
Project Number   A47A
Task Number   K
Work Unit Accession
Number   SAD 2061

6. AUTHOR(S)

Adolph Atencio, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Aeroflightdynamics Directorate, U.S. Army Aviation and Troop Command
Ames Research Center
Moffett Field, CA 94035-1000

8. PERFORMING ORGANIZATION REPORT NUMBER

A-93071

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-104016
USAATC TR-93-A-005

11. SUPPLEMENTARY NOTES

Point of Contact: Adolph Atencio, Jr., Ames Research Center, MS 210-7, Moffett Field, CA 94035-1000
(415) 604-6863

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified — Unlimited
Subject Category 08

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Helicopter handling qualities research requires that a ground-based simulation be a high-fidelity representation of the actual helicopter, especially over the frequency range of the investigation. This experiment was performed to assess the current capability to simulate the UH-60A Black Hawk helicopter on the Vertical Motion Simulator (VMS) at NASA Ames, to develop a methodology for assessing the fidelity of a simulation, and to find the causes for lack of fidelity. The approach used was to compare the simulation to the flight vehicle for a series of tasks performed in flight and in the simulator. The results show that subjective handling qualities ratings from flight to simulator overlap, and the mathematical model matches the UH-60A helicopter very well over the range of frequencies critical to handling qualities evaluation. Pilot comments, however, indicate a need for improvement in the perceptual fidelity of the simulation in the areas of motion and visual cuing. The methodology used to make the fidelity assessment proved useful in showing differences in pilot work load and strategy, but additional work is needed to refine objective methods for determining causes of lack of fidelity.

14. SUBJECT TERMS

Helicopter, Handling qualities, Simulation, Validation

15. NUMBER OF PAGES

320

16. PRICE CODE

A14

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		